GLOTTAL AIRFLOW CHARACTERISTICS OF ADULT MEN AND WOMEN AS A FUNCTION OF AGE AND INTENSITY LEVEL

By

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The present study was conducted to examine the effects of age and intensity level upon selected acoustic and aerodynamic measures of vocal fold function. Subjects included four groups of 28 individuals: young men aged 20-30 years, young women aged 20-30 years, elderly women aged 65-75 years, and elderly men aged 65-75 years. Subjects were asked to sustain the vowel / / at both a comfortable and loud intensity level. Measurements derived from the glottal airflow waveform included: fundamental frequency (F_0), fundamental frequency standard deviation, peak glottal airflow, minimum glottal airflow, alternating glottal airflow (AC flow), maximum flow declination rate (MFDR), and the ratio of minimum flow to peak flow (DC/PK). The results of the study revealed a significant decrease in F_0 for women with age but no change for men. No significant age-related effect was found for any of the remaining measures. With regard

to intensity, women demonstrated a significant increase in Fo with increased intensity while men demonstrated a significant increase in AC flow and MFDR. These results suggest possible sex-related differences in the mechanisms used to increase vocal loudness.

CHAPTER 1
INTRODUCTION

Biological aging is described as "the manifestation of the sum of a multitude of biological decrements that occur after sexual maturation" (Hayflick, 1989, p. 8). Normal aspects of aging include hair loss, reduced exercise capacity and stamina, wrinkled skin, reduced visual acuity, memory lapses, etc. (Hayflick, 1989). The process of aging also brings about changes in vocal quality. The ability of listeners to predict an individual's age based on his/her voice has been well documented (Ptacek & Sander, 1966a; Ryan & Burk, 1974; Shipp & Hollien, 1969). These studies indicate that specific voice characteristics, such as increased hoarseness, voice breaks, voice tremor, breathiness, decreased fundamental frequency, and increased pitch variability (Benjamin, 1981; Honjo & Isshiki, 1980; Linville & Fisher, 1985a; Ryan & Burk, 1974) are strong predictors of chronological age. These perceivable differences are thought to result from physiological aging of the phonatory system.

The effects of age are apparent in all structures of the larynx (Kahane, 1987; Morrison, Rammage, & Nichol, 1989). For example, ossification and calcification of the laryngeal cartilages are present in older individuals (Casiano, Ruiz, & Goldstein, 1994; Kahane, 1980; 1987). The vocal folds themselves undergo significant changes, including discoloration, atrophy, and edema (Kahane, 1990; Honjo & Isshiki, 1980; Mueller, Sweeney, & Baribeau, 1984). Possible disruptions in laryngeal innervation and

blood supply to the laryngeal nerves have been noted (Kahane, 1990), as well as atrophy and/or degeneration of the laryngeal mucosal glands (Kahane & Gracco, 1992).

Additional changes occur within the respiratory mechanism that may impact phonatory function. Janssens and colleagues (Janssens, Pache, & Nichod, 1999) noted that there are three significant physiological changes that occur with aging which affect the respiratory function. These alterations include a decrease in the elastic recoil of the lungs, a decrease in the compliance of the chest wall, and a decrease in the strength of the respiratory muscles. The net effect of these changes is to reduce the efficiency of respiration in elderly individuals (Campbell & Lefrak, 1978). Reduced respiratory efficiency has been shown to impair normal phonatory function, particularly in elderly individuals (Hoit & Hixon, 1987; Ptacek & Sander, 1966b; Ramig, Countryman, Thompson, & Horii, 1995).

Age-Related Changes in the Larynx

Cartilages. The cartilaginous structures within the larynx undergo significant change with increasing age. Calcification (Malinowski, 1967; Mueller, Sweeney, & Baribeau, 1984) and ossification (Chamberlain & Young, 1935; Hately, Evison, & Samuel, 1965; Kahane, 1980; 1983; Roncollo, 1948) of the hyaline cartilages of the larynx have been well documented. The elastic cartilages of the larynx, including the epiglottis and the apices and vocal processes of the arytenoids, do not ossify (Ardan, 1965; Kahane, 1983). The differential ossification of laryngeal cartilages results from the different fiber types that are present. Hyaline cartilages are composed of very thin, dense collagenous fibers while elastic cartilages are composed of dense elastic fibers (Colton & Casper, 1996).

Specifically, the hyaline cartilages of the larynx undergo endochondral ossification, which consists of replacement of pre-existing cartilage by bone derived from osteoblasts (Kahane, 1980). This process of ossification generally occurs earlier in age and to a greater extent in men than in women (Kahane, 1987). Laryngeal ossification begins in the mid to late 20's for men and in the 30's for women, and continues well into adulthood (Kahane, 1980; 1981; Pressman & Kelemann, 1955). In general, the thyroid and cricoid cartilages undergo the greatest extent of ossification, with partial ossification of the arytenoids occurring within the body and muscular processes (e.g., Kahane, 1981; Morrison et al., 1989).

Ossification of the thyroid cartilage results in increased stiffness of this cartilage. This increased stiffness may contribute to a reduction in nonmuscular forces in the larynx involved in returning the larynx to its resting position following respiration and effortful closure of the larynx (Fink, 1974; 1975, cf. Kahane, 1980; 1983). Additionally, increased stiffness of the thyroid cartilage may limit the extent to which thyroid compression may assist regulation of fundamental frequency (Zenker & Zenker, 1960, cf. Kahane, 1980; 1983).

Cricoarytenoid joint. Conflicting evidence regarding the effects of aging upon the cricoarytenoid (CA) joint has been reported. Casiano, Ruiz, and Goldstein (1994) found no significant changes associated with aging while Kahane and colleagues (Kahane, 1988; Kahane & Hammons, 1987; Kahn & Kahane, 1986) reported thinning and irregularity of the articular surfaces of the CA joint. Kahane (1988) observed that these degenerative changes occurred to a greater extent in male larynges, and may hinder CA joint movement during approximation of the vocal folds. Restricted CA joint movement

may thus result in incomplete closure. Kahane (1988) also noted subtle age-related changes in the synovial tissue of the CA joint, including weakening of the underlying supportive connective tissue. He suggested that changes in the synovial fluid "contributed to involution of the articular cartilage." Additionally, Segre (1971) reported loosening of the ligaments of the joint capsule. It is thought that the combined effect of these changes reduces effortful closure of the glottis involving nonmuscular forces (e.g., and decreases overall pitch range through limitation of cricothyroid movement (e.g., see Kahane, 1983).

Intrinsic laryngeal muscles. Atrophy and degeneration of the laryngeal musculature have been reported (Bach, Lederer, & Denolt, 1941; Guindi, Michaels, Bannister, & Gibson, 1981; Kahane, 1990), with the most marked changes occurring in the posterior cricoarytenoid (PCA) muscle (Bach et al., 1941; Gambino, Malmgren, & Gacek, 1990). Rodeño, Sanchez-Fernandez, and Rivera-Pomar (1993) found differential effects of aging for the PCA and thyroarytenoid (TA) muscles. Specifically, they reported that the TA muscles exhibited an increase in the percentage of type I and a decrease in the percentage of type II muscle fibers. The finding of a high percentage of type II fibers in the TA indicates a rapidly contracting muscle with sphincteric function. Therefore, loss of type II fibers in the TA muscle with age might reduce the ability of this muscle to close the glottis.

In contrast to the TA muscle, the PCA muscle demonstrated a decrease in the percentage of type I fibers and an increase in the percentage of type II fibers. Rodeño et al. considered this muscle to be a "special inspiratory one," based on the higher proportion of type I fibers observed, which indicate slow contractile properties and

increased fatigue resistance. A decrease in type I fibers in the PCA muscle may affect the inspiratory process. The loss of type I fibers indicates that this muscle may become more susceptible to the effects of fatigue, thus hampering the ability of the vocal folds to abduct during inhalation. This increased fatigue level may help contribute to a reduction in the volume of air inhaled, thus reducing the amount of air available for speech and other activities. Gambino et al. (1990), however, reported no significant changes in the neuromuscular junction of the PCA. In agreement with Rodeño et al. (1993), Gambino and colleagues concluded that aging affects this muscle differentially.

Conflicting evidence exists concerning the effect of aging upon contractile properties of the TA muscle. Through animal studies, Mardini and colleagues (Mardini, McCarter, Neal, Wiederhold, & Compton, 1987) reported only minor differences in TA muscle activity between young and old baboons. Specifically, they noted that although the TA muscles of the older baboons contracted less rapidly and required increased recovery time, their ability to generate maximum active tension increased relative to that of the TA muscles of the younger baboons. Mardini et al. (1987) generalized the results of this animal study to account for human laryngeal changes in elderly individuals and concluded that the perceived vocal effects of aging were not due to changes in TA muscle activity. Rather, the authors suggested that other morphological alterations of the vocal folds or differences in sensory innervation of the larynx between young and elderly individuals might account for the perception of an elderly voice.

Studies focused on the contractile properties of the TA muscle in humans have also reported differences in TA muscle activity between young and elderly adults (Baker, Ramig, Luschei, & Smith, 1998; Luschei, Ramig, Baker, & Smith, 1999). Baker et al.

(1998) reported significantly reduced levels of muscle activity, as characterized by lower EMG amplitude, in the TA muscle of elderly adults. Luschei et al. (1999) reported decreased firing rates in elderly individuals, as well as increased variability in the firing rate of the TA muscle in elderly men but not in elderly women. Luschei and colleagues suggested that reduced TA activity may be related to the age-related changes noted in voices of elderly men.

Vocal folds. The vocal folds are composed of three primary layers: the epithelium, the lamina propria, and the vocalis muscle (Hirano, 1974). The lamina propria is divided into three layers: superficial, intermediate, and deep. The epithelium and the superficial layer of the lamina propria, which form the mucosal cover of the vocal folds, are critical during vibration of the vocal folds. Age-related alterations in the appearance, structure, and composition of the majority of these layers have been documented. In both men and women, the thickness of the epithelium increases until approximately 70 years of age. After age 70, the epithelium becomes thinner in men but continues to increase in thickness for women (Hirano, Kurita, & Sakaguchi, 1989). The attachment between the epithelium and the lamina propria loosens (Kahane, 1990) and the superficial layer of the lamina propria becomes thicker and edematous (Hirano et al., 1983). The elastic fibers within the superficial layer of the lamina propria change in size, become disorganized, and undergo metabolic changes, resulting in changes in stiffness and viscoelasticity of the vocal fold cover (Sato & Hirano, 1997). Hence, changes in the vibration of the vocal folds may occur. Additionally, there is a decrease in the number of and activation of fibroblasts within the macula flava of the superficial layer (Sato & Hirano, 1995). Since the macula flava are responsible for regulation of the fibrous

component of the vocal ligament, they play an important role in the vibratory mechanism (Sato & Hirano, 1995). Impairment in the ability of the macula flava to regulate the fibrous component of the vocal ligament may affect the stiffness and viscoelasticity of the vocal fold, thus resulting in reduced amplitude of vibration (Sato & Hirano, 1995; 1997).

The intermediate layer of the lamina propria thins with age. Atrophy of the elastic fibers occurs in conjunction with reduced density (Hirano et al., 1989; Kahane, 1983, 1987; Sato & Hirano, 1997). In contrast, the deep layer of the lamina propria increases in thickness. The collagenous fibers increase in size and density but also exhibit increased disorganization (Hirano et al., 1983).

Similar to the pattern noted for cartilaginous ossification, changes in the lamina propria are more extensive in the male than in the female. It has been suggested that changes in the lamina propria may contribute to vocal fold bowing and irregularities on the vibratory surfaces of the vocal folds. As a result, incomplete vocal fold approximation may occur with subsequent changes in vocal quality (Kahane, 1990).

Mucosal glands. Little evidence exists concerning the effect of aging upon the mucosal glands that serve to lubricate and protect the laryngeal mechanism (Kahane, 1990). A few investigators have reported atrophy and degeneration of the mucosal glands with advancing age (e.g., Gracco & Kahane, 1989; Kahane & Gracco, 1992; Sato & Hirano, 1998), while others have found no significant age-related differences (Bak-Pedersen & Nielsen, 1986; Hirano et al., 1983). Sato and Hirano (1998) noted a reduction in the amount of glandular secretions as well as changes in the quality and viscosity of the secretions. They suggested that such changes may affect the lubrication

of the vocal folds and subsequently contribute to vocal aging. Decreased lubrication of the laryngeal mucosa, specifically the epithelium, would increase the stiffness of the cover, thereby reducing vibratory amplitude and possibly contributing to increased instability of fundamental frequency (Gracco & Kahane, 1989). Gracco and Kahane suggested that this decrease in vocal fold hydration may be a factor in the increased fundamental frequency commonly observed in elderly men, as well as contributing to increased instability of fundamental frequency. In women, the effect of increased fundamental frequency may be offset by increased vocal fold edema, thus resulting in a decrease in fundamental frequency for women.

Innervation. Few studies have been conducted to examine the effects of aging upon laryngeal innervation. Malmgren and colleagues examined age-related changes in both the recurrent laryngeal nerve (Malmgren & Ringwood, 1988) and the superior laryngeal nerve in rats (Rosenberg, Malmgren, & Woo, 1989). In the superior laryngeal nerve (SLN) of rats, there was an increase in the presence of internodal myelin bubbles, with thinning of the myelin occurring in such areas. There was no significant difference in the number of myelinated fibers, although there was a nonsignificant trend for the number of unmyelinated fibers to increase with age (Rosenberg et al., 1989). In contrast, Mortelliti, Malmgren, and Gacek (1990) observed a loss of myelinated fibers in conjunction with age-related fiber loss in the human SLN. A significant decrease in the number of myelinated fibers with small axonal diameters was also observed. Mortelliti et al. (1990) suggested that the decrease in the number of myelinated fibers may contribute to the increased threshold of the laryngeal protective reflex observed in elderly individuals.

In the recurrent laryngeal nerve (RLN), there was an increase in the number of completely degenerated fibers found, changes in the number of medium and large myelinated fibers, and an increase in the number of fibers with abnormally thin myelin (Malmgren & Ringwood, 1988). Degeneration of fibers of the recurrent laryngeal nerve may contribute to atrophy of the vocal fold musculature. A comparable study of the human RLN has not been completed.

Blood supply. Evidence suggests that there are age-related changes in the blood supply to the laryngeal nerves. As discussed by Kahane (1990), these changes include thickening of the capillary walls and a reduction in the diameter of the blood vessels (Ferreri, 1959; Hommerich, 1972). It has been suggested that alterations in blood supply may be responsible for the degeneration of RLN fibers (Malmgren & Ringwood, 1988). Degeneration of nerve fibers would lead to subsequent muscle atrophy.

Age-Related Changes in the Respiratory System

The respiratory system serves as the "driving force" behind phonation. Impairment of, or improper usage of the respiratory system results in reduced phonatory abilities (Hoit, Banzett, & Brown, 2002; Murdoch, Chenery, Bowler, & Ingram, 1989; Solomon & Hixon, 1993). Hence, it is important to consider the changes that occur within the respiratory system with age and their impact upon voice production.

Structural changes. Several changes occur in the respiratory structures as a result of aging (Kahane, 1981). A commonly observed structural change is the development of kyphosis, which is defined as "an anterior curvature of the verterbral column in the thoracic and sacral regions" (Stedman's Medical Dictionary, 2001). Kyphosis results in increased concavity and anterior-posterior narrowing of the thorax as a result of thinning

and degeneration of the vertebral discs (Kahane, 1981), and has been reported in up to 68% of elderly individuals (Edge, Millard, Reid, & Simon, 1964). Increased rigidity is also evident in the thorax, due to in part to changes in the ribs and the costal joints. Ossification of the ribs and costal cartilages has been observed in elderly men and women (Edge et al., 1964; Kahane, 1981). Movement of the ribs is therefore limited due to compression of the thorax and calcification of costal cartilage and rib-vertebral articulations (Kahane, 1981; Murray, 1986, cf. Janssens et al., 1999). Increased stiffness of the thoracic components limits the extent to which the thorax can be displaced, thus reducing lung expansion. Decreased lung expansion reduces the amount of pressure generated during inspiration and subsequently reduces the volume of air inspired. Furthermore, the increased stiffness of the thorax results in an increased relaxation pressure in the chest wall, which contributes to a smaller volume of air available for use (Janssens et al., 1999).

The respiratory muscles also undergo significant changes with age. The shape of the diaphragm may change as a result of thoracic compression and become flat (Edge et al., 1964). A mild to moderate reduction in diaphragmatic strength, as measured by transdiaphragmatic pressure, has been observed in elderly men (Polkey, Harris, Hughes, Hamnegard, Lyons, Green, & Moxham, 1997; Tolep, Higgins, Muza, Criner, & Kelsen, 1995). In addition, a decrease in the cross-sectional area of muscle fibers has been reported for both the internal and external intercostals, although the internal intercostals appear to be affected to a greater extent. The decline in muscle fibers of the internal intercostals may contribute to the reduction in forced expiratory volume observed in elderly speakers (Mizuno, 1991).

Decline in respiratory muscle strength is reflected in a variety of respiratory measures. Black and Hyatt (1969) reported a significant decrease in maximal expiratory pressure (Pe) for men 55 to 70+ years of age, while women aged 55 to 70+ years demonstrated a significant decrease in maximal inspiratory pressure (Pi). Schmidt, Dickman, Gardner, and Brough (1973) noted age-related declines for both men and women on measures of Pe, forced vital capacity (FVC), and forced expiratory volume in 1 second (FEV_1).

In contrast, Burrows and colleagues (Burrows, Cline, Knudson, Taussing, & Lebowitz, 1983) reported significant declines in FVC and FEV_1 for women after the age of 35 years, with an accelerated decline at 55-65 years of age. This accelerated decline was not observed in men. Burrows et al. attributed this difference to a subtle survivor effect, and proposed that a similar decline in pulmonary function in men would be observed in longitudinal studies. Indeed, Ware and associates (Ware, Dockery, Louis, Xu, Ferris, & Speizer, 1990) demonstrated that the rate of decline in pulmonary function occurred twice as fast in their longitudinal studies as compared to previous cross-sectional studies. To summarize, the weakening of the respiratory muscles combined with the increased rigidity of the chest wall makes respiration and generation of adequate pressure more difficult for elderly individuals (Campbell & Lefrak, 1978).

The aging process appears to have a significant effect upon the lungs. Evidence suggests a reduction in size, weight, and elasticity (Richards, 1965; Rolleston, 1922, cf. Linville, 2001). In contrast, lung compliance increases with age (Lynne-Davies, 1977). A decrease in collagen content in the lung parenchyma with age has also been observed (Andreotti, Bussotti, Cammelli, Aiello, & Sampognaro, 1983) while an increase in elastin

content in the interlobular septa, the pleura, and possibly the bronchii have been reported (Pierce & Ebert, 1965). The combination of decreased elasticity and increased compliance reduces the efficiency with which air is expelled from the lungs during normal expiration (Lynne-Davies, 1977), resulting in a reduction in recoil pressure in the lungs. This reduction in lung recoil pressure contributes to age-related declines in Pe, FVC, and FEV_1.

Additional changes contribute to reduced respiratory efficiency. The opening into the alveolar ducts increases the diameter of the alveolar ducts in conjunction with a widening and shallowing of the alveoli. These alterations reduce the extent of supporting tissue around the airways and may lead to collapse of the smaller airways during respiration (Janssens et al., 1999).

Functional changes. The aging process affects respiratory function differentially in men and women. Interestingly, much of the evidence supports a greater effect of aging upon respiratory function in women compared to men. This pattern contrasts with that observed for laryngeal aging, in which men are affected to a much greater extent.

For both men and women, total lung capacity (TLC) remains unaffected by age (Hoit & Hixon, 1987; Levitzky, 1984). TLC is defined as the volume of gas that is in the lungs following maximum inspiration, and is determined by two actions: the strength of the inspiratory muscles and the inward elastic recoil forces of the lungs and chest wall (Levitzky, 1984). Apparently, the balance of alterations between these two forces remains relatively constant throughout the lifespan (Linville, 2001). In a similar fashion, inspiratory capacity (the largest volume of air inspired from resting expiratory level [REL]) and functional residual capacity (the volume of air in lungs and airways at REL)

do not change with age in either men or women (Hoit & Hixon, 1987; Hoit, Altman, & Morgan, 1989). In contrast, residual volume [RV] (the volume of air remaining in the lungs following maximum expiration) increases with age. This increase in RV presumably occurs due to increased stiffness of the chest wall combined with reduced recoil pressure of the lungs, resulting in a larger volume of air being trapped in the lungs (Leith & Mead, 1967; Janssens et al., 1999).

The remaining measures of respiratory function exhibit differences relative to age and sex. Vital capacity [VC] (the volume of air that can be expired following maximum inspiration) and expiratory reserve volume [ERV] (the largest volume of air that can be expired from REL) remain relatively unchanged for elderly men (Hoit & Hixon, 1987). In women, however, both VC and ERV decrease with age (Hoit et al., 1989). This difference in VC and ERV between men and women may be due to the greater decline in respiratory function that women experience as they age (Linville, 2001).

These measures of respiratory function are frequently expressed as a percentage of TLC, in order to account for physical/size differences between men women. These normalized values continue to show trends similar to absolute measures of lung function. For example, both elderly men and women exhibit increases in residual volume/total lung capacity (RV/TLC) compared to younger speakers (Hoit & Hixon, 1987; Hixon et al., 1989). Expiratory reserve volume/total lung capacity (ERV/TLC) remains unchanged for elderly men but decreases for elderly women. For vital capacity/total lung capacity (VC/TLC), however, both elderly men and women exhibit a reduction compared to younger speakers. This pattern contrasts with the relative constancy of non-normalized

VC in elderly men. Finally, elderly women demonstrate a greater percentage of rib cage contribution to respiration than elderly men (Hoit & Hixon, 1987; Hoit et al., 1989).

In a similar fashion, VC decreases in relation to functional residual capacity (FRC), defined as the volume of air remaining in the lungs following passive expiration (Levitzky, 1984). Due to decreased lung elasticity, the ability of the lungs to return from an inflated to a resting state is impaired (Kahane, 1981; Lynne-Davies, 1977). Consequently, an increased volume of air remains in the lungs following expiration, leading to an increase in FRC (Lynne-Davies, 1977). Elderly individuals therefore breathe at higher lung volumes than do younger individuals (Janssens et al. 1999).

The sum of all these changes is that the overall efficiency of the respiratory system is reduced. Most notably, the reduction in VC for elderly speakers indicates a smaller volume of air is available for acts requiring volitional expenditure of air, i.e., speech production (Hoit & Hixon, 1987). Hence, the impact of these changes upon speech breathing will be considered.

Age-Related Changes in Speech Breathing

The effect of age upon speech breathing has been explored during both spontaneous speech and oral reading (Hoit & Hixon, 1987; Hoit et al., 1989; Sperry & Klich, 1992). The results of these studies suggest that aging has a greater effect upon speech breathing in men during spontaneous speech production compared to oral reading. The effect of the aging process upon speech breathing in women appears to be more widespread, and is apparent during both spontaneous speech and oral reading.

Measures obtained during spontaneous speech tasks show age-related increases in lung volume excursion (LVE), rib cage volume initiation referenced to relaxation rib

cage volume (RCVI-R), and percent vital capacity expired per syllable (%VC/syllable) for men (Hoit & Hixon, 1987). Elderly men also produced fewer syllables per breath group during unstructured speaking tasks (Hoit & Hixon, 1987).

In contrast to spontaneous speech production, oral reading resulted in few differences between young and elderly men. Percent vital capacity per syllable was greater in elderly males than younger males; all other measures related to speech breathing were not significantly different between the two age groups (Hoit et al., 1989).

Unlike the results obtained for men, studies conducted on speech breathing in women have demonstrated an age-related effect on speech breathing during both spontaneous speech and oral reading. During both types of tasks, elderly women demonstrated greater LVE, RCVI-R, and %VC/syllable during both spontaneous speech and oral reading compared to younger women (Hoit et al., 1989; Sperry & Klich, 1992). Lung volume initiation referenced to relaxation lung volume (LVI-R) was also greater for elderly women compared to their younger counterparts during spontaneous speech while rib cage volume excursion was greater during oral reading for the elderly women (Hoit et al., 1989).

Finally, Hoit et al. (1989) reported that the number of syllables per breath group was not significantly altered by age for either task for elderly women. These results differ from those reported by Sperry and Klich (1992), who found increased frequency of inhalation during oral reading for elderly women. These results suggest that fewer syllables per breath group would be produced by the elderly speakers.

As discussed by Hoit and Hixon (1987), the increase in age-related effects observed in men during spontaneous speech suggests that some speakers are able to make

the necessary linguistic and respiratory adjustments to compensate for reduced efficiency of the phonatory and respiratory systems. These differences may not be apparent during reading tasks that are more structured relative to sentence length but may become more apparent during spontaneous speech. Mitchell, Hoit, and Watson (1996) suggested that the decrease in the number of syllables per breath produced and increased lung volume expenditure observed in spontaneous speech may be due to the added stress of cognitive-linguistic processing. Such a finding may help explain the task difference observed for elderly men.

In contrast, elderly women demonstrated similar changes with age during both spontaneous speech and reading. Therefore, the changes in speech breathing observed with age in women may be more directly related to general respiratory decline and poor laryngeal control of pulmonary airflow (Sperry & Klich, 1992).

Laryngoscopic Characteristics of Aged Vocal Folds

Laryngoscopic studies have demonstrated a number of visible and functional changes in the vocal folds with age. A yellowish or dark grayish discoloration of the vocal folds has been observed endoscopically in elderly speakers 67 to 86 years of age (Honjo & Isshiki, 1980; Linville, Skarin, & Fornatto, 1989), with edema being more prevalent in women (74%, Honjo & Isshiki, 1980) and vocal fold atrophy more commonly seen in elderly men (67%, Honjo & Isshiki, 1980).

A persistent glottal gap (space between the vocal folds during the closed phase of the vibratory cycle) has been observed in both elderly men and women (Honjo & Isshiki, 1980; Linville et al., 1989). Videostroboscopic studies have demonstrated differences between young and elderly women's vocal folds movement. Biever and Bless (1989)

observed aperiodicity, reduced amplitude of vibration, a reduced mucosal wave, and stiffness to a greater degree in elderly women aged 60 to 77 years. They also reported incomplete glottal closure in both elderly (90%) and young women (80%). While a posterior glottal gap was prevalent in both groups, a mid-membranous or anterior glottal gap was present only among the elderly women. Biever and Bless concluded that the presence of a posterior glottal gap was a normal occurrence among women, regardless of age. The presence of a mid-membranous or anterior gap, however, suggested "a decrease in muscle mass and thinning of the intermediate layer of the lamina propria [Hirano et al., 1983]" (Biever & Bless, 1989, p. 127).

Similar results were obtained by Linville (1992), in comparing young (21 to 23 years) versus elderly (72 to 87 years) women using videostroboscopy. She noted that the young women exhibited a posterior glottal gap and incomplete glottal closure significantly more frequently than the elderly women did. Among the elderly women, however, an anterior gap was the most common type of gap observed, with a spindle type configuration also present. In agreement with Biever and Bless (1989), Linville suggested that the anterior gap or spindle closure seen in the elderly women indicated gaps in the membranous portion of the vocal folds. The presence of gaps in the membranous portion was thought to be the result of muscular or connective tissue atrophy, changes that have been shown to occur with age (Kahane, 1987; Kahane, 1990; Morrison et al., 1989). Similar studies on young and elderly men have not been completed.

Acoustic Measures of Vocal Aging

Several acoustic characteristics have been associated with the aged voice. Changes in fundamental frequency (F_0) have been observed for older speakers. Generally, males exhibit an increase in F_0 (Hollien & Shipp, 1972; Honjo & Isshiki, 1980; Mysak, 1959) although Benjamin (1981) noted a decrease in F_0 for elderly men as compared to younger men. Some authors have reported no significant difference in F_0 between young and elderly men (Ramig & Ringel, 1983; McGlone & Hollien, 1969; Wilcox & Horii, 1980). For women, a decrease in F_0 has been observed with advanced age (Awan & Mueller, 1992; Benjamin, 1981; Honjo & Isshiki, 1980). Similarly, a lower mean speaking fundamental frequency (SFF) has been reported for elderly women (Brown, Morris, Hollien, & Howell, 1991; Russell, Perry, & Pemberton, 1995). In some studies, a lack of significant difference in F_0 between young and elderly women appears to be due to increased F_0 variability for the elderly speakers (Biever & Bless, 1989; McGlone & Hollien, 1969; Wilcox & Horii, 1980). This increased variability in several acoustic measures has been well documented and may contribute to the difficulties in finding significant differences between groups (Benjamin, 1981; Biever & Bless, 1989; Brown, Morris, & Michel, 1989, 1990; Linville & Fisher, 1985; Linville, Korabic, & Rosera, 1990; Mysak, 1959, Wilcox & Horii, 1980).

Contradictory evidence exists regarding measures of frequency and intensity perturbation. Some amount of variation in the acoustic signal is normal, and may be due to variations in muscle tension, small fluctuations in subglottic pressure, air flow, or muscle tension (Gelfer, 1995). Jitter, defined as "cycle-to-cycle variation in fundamental frequency" (Kent & Read, 1992, p. 58), is often used as a measure of frequency

perturbation. Although several authors have reported increased jitter values for elderly speakers (Benjamin, 1981; Linville & Fisher, 1985; Orlikoff, 1990; Wilcox & Horii, 1980), others have reported no significant age-related differences (Biever & Bless, 1989; Brown et al., 1989; 1990; McGlone &Hollien, 1969; Ramig & Ringel, 1983). However, Ramig and Ringel (1983) noted that jitter values were greater in elderly speakers in poor physical condition compared to elderly speakers in good physical condition. Linville and Fisher (1985) also reported that removal of extreme values resulted in similar jitter ratios for all three age groups in their study (young, middle-aged, and elderly). They concluded that "....although jitter values tend to show more variability in older women than younger women, elderly women, on the average, do not display more jitter than younger women" (p. 327). Hence, measurements of jitter may not be a reliable means of discriminating young from elderly speakers.

In contrast, Linville & Fisher (1985b) demonstrated that elderly women exhibited significantly less F_0 stability as indicated by greater fundamental frequency standard deviation (F_0 SD) values and increased variability compared to the younger groups. This difference did not appear to be due to extreme values. F_0 SD values were found to increase significantly after middle age, indicating that "frequency stability, as measured by F_0 SD, was found to decrease significantly after middle age." (p. 327). Therefore, while age-related differences have not been observed among jitter-related measures of frequency perturbation, stability of F_0 during phonation does appear to decline with advancing age, at least according to Linville and Fisher. The measurement of F_0 SD appears to be sensitive to the effects of age upon phonatory function, whereas jitter is not. Jitter has been shown to be affected by both frequency and intensity (Gelfer, 1995; Lee,

Stemple, & Kizer, 1999), as well as vocal tract configuration (Lin, Jiang, Noon, & Hanson, 2000), all of which may differ among individuals of the same or different ages. Hence, the use of jitter does not appear to be a reliable or valid means to differentiate among individuals of various ages.

Measures of intensity perturbation are frequently reported in terms of shimmer. Shimmer is defined as "the cycle-to-cycle variation in the peak amplitude of the laryngeal waveform" (Kent & Deal, 1992, p. 58). Data reported for shimmer values have been similar to those reported for jitter. While some authors have reported an increase in shimmer values for elderly speakers (Biever & Bless, 1989; Orlikoff, 1990), this increase in shimmer may be related to the overall health of the individual, as indicated by Ramig and Ringel (1983). Similar to the findings reported for jitter, Ramig and Ringel (1983) demonstrated that higher shimmer values were correlated with poor physical condition. Shimmer-related measurements, therefore, may not be effective in discriminating speakers according to age.

Aerodynamic Measures of Vocal Aging

A few studies have examined the effect of age upon phonatory airflow measures. Considering that structural and functional changes in the aging larynx are likely to affect vocal fold movement and closure, it is plausible that these alterations would be reflected in airflow measures. The results of earlier studies examining differences in airflow rates have yielded conflicting results between men and women. A decrease in laryngeal airway resistance (R_{law}) during syllable repetition has been reported for men aged 75 years or older (Melcon, Hoit, & Hixon, 1989) and a combined group of elderly men and women over the age of 75 years (Holmes, Leeper, & Nicholson, 1994). Higgins and

Saxman (1991) reported greater flow amplitude rates [defined as the difference between minimum flow and peak flow] for elderly males compared to younger men during both vowel prolongation and syllable repetition.

Age-related changes in airflow appear to be minimal for women. Biever and Bless (1989) found no significant differences in mean airflow rates during a vowel prolongation task between young and elderly women (156 cc/s vs. 151 cc/s) but noted that elderly speakers exhibited greater variability. Hoit and Hixon (1992) reported no significant change in R_{law} with increasing age in women during a syllable repetition task, although they did note that the 45 year-old women tended to have lower R_{law} values. They concluded that the reduction in R_{law} at this age was probably due to hormonal changes occurring prior to menopause. Subsequent analysis revealed that premenopausal women had a lower average R_{law} (35 cm H_20/ls) compared to postmenopausal women (46 cmH_20/ls). Similarly, Higgins and Saxman (1991) found no significant difference in flow

Table 1-1. Summary of age-related phonatory changes according to type of speech task in men and women.

Men	Women
increased average airflow rates[a,b] (syllable repetition)	no difference in average airflow rates[d] (vowel prolongation)
reduced R_{law}[a,b] (syllable repetition)	no significant change in R_{law}[e] (syllable repetition)
increased flow amplitude rates[c] (vowel prolongation, syllable repetition)	no significant difference in flow amplitude rates[c] (vowel prolongation, syllable repetition)
	no difference in glottal airflow parameters[f] (vowel prolongation)
	increased variability in average airflow rate[d] and peak glottal airflow[f] (vowel prolongation)

[a]Melcon et al. (1989), [b]Holmes et al. (1994), [c]Higgins & Saxman (1991), [d]Biever & Bless (1989), [e]Hoit & Hixon (1992), [f]Sapienza & Dutka (1996)

amplitude rates between young and elderly women during vowel prolongation and syllable repetition. Finally, Sapienza and Dutka (1996) reported no age-related differences in a variety of glottal airflow parameters for women during a vowel prolongation task, although they did observe increased variability in peak glottal airflow rates among the 70 year-old women.

In general, the results of these few studies suggest a greater impact of aging upon phonatory airflow measures for men than for women (see Table 1-1). Given that laryngeal structures appear to be affected by aging to a greater extent in men, such changes in phonatory function would be expected. Most of these studies, however, have examined airflow measures that are influenced by the entire vocal tract. With the exception of the work by Higgins and Saxman (1991) and Sapienza and Dutka (1996), few have investigated the effect of age upon airflow measures that estimate the function of the vocal folds.

Perceptual Identification of Elderly Speakers

Results of perceptual studies have shown that listeners are able to estimate the age of a speaker based on his/her voice (Linville & Fisher, 1985; Linville & Korabic, 1986) and/or distinguish young versus elderly speakers (Ptacek & Sander, 1966a; Ryan & Burk, 1974; Shipp & Hollien, 1969). Ptacek and colleagues (Ptacek & Sander, 1966a; Ptacek, Sander, Maloney, & Jackson, 1966) reported that listeners identified elderly speakers based on "phrasing, speed, hesitancy, voice breaks, and vitality." Ryan and Burk (1974) reported that listeners determined speakers to be of advanced age based on several characteristics, including vocal tremor, imprecise consonantal production, and reduced rate of articulation.

A few studies have examined vocal characteristics associated with the elderly voice. Increased hoarseness, increased occurrence of voice breaks, and lowering of vocal pitch has been perceived in elderly speakers (Benjamin, 1981; Ptacek & Sander, 1966a). Honjo and Isshiki (1980), in contrast, reported increased roughness and hoarseness in elderly women, suggesting that these changes were due to post-menopausal endocrine changes resulting in increased mass of the vocal folds. An increase in the mass of the vocal folds would not only lead to lowering of F_0, but could also contribute to increased hoarseness as the increase in mass is likely to be asymmetrical, thus altering the vibratory pattern of the vocal folds.

Specific vocal qualities have also been associated with elderly men. Ryan and Burk (1974) found that increased "laryngeal tension" and "air loss" were associated with elderly speakers during speech. The perceived air loss during phonation among elderly men would indicate increased breathiness, while the increase in laryngeal tension may be indicative of attempts by the speaker to "gain better control of an increasingly less stable sound-generating system" (Ryan & Burk, 1974, p.191).

These perceptual qualities can be related to a variety of anatomical and physiological changes that occur with age. Increased breathiness among elderly speakers is likely the result of insufficient glottal closure due to vocal fold atrophy or bowing of the vocal folds (Biever & Bless, 1989). Increased vocal hoarseness or harshness may be due to loosening of the epithelial layer over the vocal folds (Wilcox & Horii, 1980, cf. Kahane, 1990) or due to changes in vocal fold mass, as suggested by Honjo and Isshiki (1980). Vocal fold vibration may also be affected by disruptions in innervation, blood supply, and/or mucosal secretions. This disruption in vocal fold vibration could lead to

an irregular vibratory pattern, which would be perceived as vocal tremor, increased tension, hoarseness, harshness, and/or breathiness (Kahane, 1990). These perceivable changes in vocal quality have been measured objectively using phonatory airflow measures.

The Use of Aerodynamic Measures to Measure Laryngeal Function

Aerodynamic measures have long been used to assess vocal fold function during phonation. Numerous studies have been conducted on individuals with normal vocal function (e.g., Hoit & Hixon, 1992; Holmberg, Hillman, & Perkell, 1988, 1989; Netsell, Lotz, DuChane, & Barlow, 1991; Smitheran & Hixon, 1981; Stathopoulos & Sapienza, 1993a, b; 1997) as well as individuals with a variety of voice-related disorders. These latter studies have focused on individuals with adductor spasmodic dysphonia (Fisher, Scherer, Guo, & Owen, 1996; Sapienza, Crary, & Gorham, 1995; Witsell, Weissler, Donovan, Howard, & Martinkosky, 1991; Woo, Colton, & Shanghold, 1987), vocal fold paralysis (Brandenburg, Kirkham, & Koachkee, 1992; D'Antonio, Wigley, & Zimmerman, 1995; Woo et al., 1987; Woo, Colton, Brewer, & Casper, 1991), vocal fold nodules and/or polyps (Hillman, Holmberg, Perkell, Walsh, & Vaughn, 1990; Peppard, Bless, & Milenkovic, 1988; Sapienza & Stathopoulos, 1994), contact ulcers (Hillman et al., 1990), and laryngitis (Woo et al., 1987). These studies have demonstrated the usefulness of aerodynamic measurements in describing vocal fold function.

As discussed by Holmberg et al. (1988, p. 511), "vocal fold vibration results from an alternating balance between subglottal air pressure that drives the vocal folds apart and muscular, elastic, and Bernoulli restoring forces that draw them together (Stevens, 1977; Baer, 1981)." The vibrating vocal folds then "act as a variable valve that allows quasi-

periodic pulses of air to escape from the lungs into the tract. These air 'puffs' produce an impulsive excitation of the acoustical conduit constituting the vocal tract" (Flanagan, 1958, p. 99). By describing the characteristics of the waveform that is emitted during each vibratory cycle, investigators have been able to describe features associated with both normal and pathologic voice.

Non-invasive measures of airflow and subglottal pressure were initially obtained by measuring the velocity of air flowing through the lips (e.g., see Woo et al., 1987). Smitheran and Hixon (1981) described a non-invasive technique for estimating subglottal air pressure and average airflow. During production of the syllable /pɑ/, airflow generated during phonation was channeled through a respiratory face mask to a pneumotachograph, while air pressure behind the lips was sensed through a small, polyethylene tube that also passed through the face mask. Estimates of subglottal pressure were obtained by measuring the peaks of intraoral pressure produced during the /p/ portion of the syllable /pɑ/. Articulation of the voiceless phoneme /p/ necessitates closure of the lips and velopharyngeal port, and abduction of the vocal folds. During this phase, pressures within the vocal tract are equivalent, such that intraoral air pressure equilibrates subglottal pressure. Thus intraoral air pressure can be used as an estimate of subglottal pressure.

Smitheran and Hixon (1981) noted further that by using a repetitive utterance produced at the rate of 1.5 syllables per second (e.g., /pɑpɑpɑ/), laryngeal valving adjustments would naturally occur in a consistent order due to the "aeromechanical scheme associated with the production of certain speech-sound subsets of the English language" (p. 139). The consistency of these adjustments would allow for "discontinuous

estimates" of subglottal pressure during voice vowel segments, by interpolation between successive peak intraoral pressures associated with /p/. As discussed by Lofqvist and colleagues (Lofqvist, Carlborg, & Kitzing, 1982) this estimation should be performed on the mid-portion of the vowel segment. By measuring the mid-portion of the vowel, the authors reported that chances of measurement being influenced by airflow associated with aspiration during the release of the stop plosive were minimized.

Measurement of translaryngeal airflow can also be made during the mid-portion of the vowel segment of the syllable /pɑ/. Since the only constriction point during the production of vowels would be at the level of the larynx, oral airflow measures are assumed to be representative of translaryngeal airflow. The ratio of subglottal pressure to airflow is calculated as an added measure of laryngeal airway resistance and is used to describe vocal fold function during phonation.

Average measures involving translaryngeal airflow, estimated subglottal pressure, and laryngeal airway resistance can be viewed as "gross" measures of laryngeal aerodynamics (Scherer, 1991). Such measures generally do not account for the effect of supraglottal vocal tract resonances upon the sound pressure or airflow rate measured at the lips. Inverse-filtering, however, compensates for the vocal tract resonances by passing the recorded waveform though a filter. The filter "has a transfer characteristic that is the inverse of the transfer characteristic of the supraglottal vocal tract configuration at the moment [of phonation]" (Rothenberg, 1973, p. 1632). The influences of the upper vocal tract resonances are cancelled, and the remaining waveform is assumed to represent glottal airflow.

Rothenberg (1977) developed a circumferentially-vented respiratory facemask that improved the acquisition of airflow data. Previously, measurements were obtained by funneling the airflow through a wire screen via a face mask. The use of this type of mask resulted in effective lengthening of the vocal tract as well as distortion of the radiated speech signal due to the use of a single channel through which airflow rates were measured. The ability of the mask to respond to high frequencies was also limited, since the distance between the mouth and the channel through which airflow was measured would result in a slight delay between actual measurement of the airflow and the time at which the airflow passed through the lips. In the mask developed by Rothenberg (1977), flow vents were placed around the circumference of the mask that reduced the distortion of the radiated speech signal and improved the high frequency response characteristic of the mask. This design also eliminated or minimized the build-up of condensation on the flow vents, a problem frequently encountered with other types of masks. The use of a circumferentially-vented face mask in conjunction with inverse-filtering has allowed for improved examination of glottal airflow. In addition, development of computerized software (e.g., *CSpeech*, Milenkovic, 1992; *TF32*, Milenkovic, 2001) has made the clinical application of this method more feasible.

Specific aerodynamic measures can be used to reflect the status of vocal fold function during voice production. These measures are used as indices of vocal fold function and the manner in which pulmonary airflow is modulated at the level of the vocal folds. Analysis of the data obtained from these measurements in the present study should provide information concerning the extent to which vocal fold vibration is affected by age.

Speech Tasks

Sustained phonation is frequently used in studies of vocal fold function as it represents a stable method of phonation from which various acoustic and aerodynamic measures can be obtained. Since several authors have reported increased variability for both acoustic and aerodynamic measures for elderly speakers (e.g., Decoster & Debruyne, 1997; Linville, 1988; Linville & Fisher, 1985b; Linville et al., 1990; Orlikoff, 1990; Ramig & Ringel, 1983; Sapienza & Dutka, 1996), sustained vowel production was chosen in order to assess the stability of phonation in elderly speakers.

The use of a sustained vowel task also provides a uniform method of phonating for all speakers. Several studies have demonstrated significant differences in selected airflow measures as a result of the type of speech task. Use of a sustained vowel task eliminates possible influences from co-articulatory movements associated with a connected speech task. With regard to speech task effects, Higgins and Saxman (1993) reported greater flow amplitude rates for sustained phonation compared to syllable repetition tasks for both normal young and elderly adults, as well as higher F_0 values for elderly women. Netsell, Lotz, and Shaughnessy (1984) reported unsystematic variations in average airflow rates between sustained vowel production and syllable repetition for dysphonic patients. More recently, Sapienza and Stathopoulos (1995) reported significantly higher maximum flow declination rates (the maximum rate of decrease in airflow), sound pressure level, and F_0 for sustained phonation compared to reading or syllable repetition. These task-related differences are thought to be due to the effects of co-articulatory adjustments during connected speech upon laryngeal height, tongue height, and vocal fold tension (Higgins & Saxman, 1993; Honda, 1983; Sapienza &

Stathopoulos, 1995). Hence, the use of a sustained phonation eliminates possible co-articulatory influences associated with connected speech, allowing for a more focused examination of vocal fold function. Given that significant changes in supraglottal articulatory structure and function are known to occur with advancing age (e.g., Kahane, 1990), it is particularly necessary in the present study, which is concerned with the effects of aging upon vocal fold function, that such influences are minimized.

The sustained phonation task in this study was performed at two loudness levels: comfortable and loud. Previous research has demonstrated differences in selected aerodynamic measurements between adults and children and the mechanisms used to alter the loudness level of the voice (Stathopoulos & Sapienza, 1997). Additionally, recent evidence suggests that the ability of elderly adults (68-79 years) to regulate vocal loudness is hindered by a weaker and less efficient laryngeal valving system (Baker, Ramig, Sapir, Luschei, & Smith, 2001). Due to the physiological differences between young and elderly speakers, it was predicted that older speakers would utilize different mechanisms to increase the loudness level of their voices as compared to their younger counterparts.

Summary

In conclusion, there appears to be a need for continued examination of the effect of aging upon phonatory function. Conflicting evidence exists concerning the effect of the aging process upon phonatory function. Possible reasons for the conflicting results may be due to individual subject variables, such as overall health, that may have influenced the outcome of these studies. In the present study, strict inclusion and

exclusion criteria were utilized in the selection of subjects to insure a representative sample of healthy young and elderly men and women.

In addition, most of the studies regarding age and airflow rates have focused primarily on women. Evidence suggests that the anatomical effects of aging are more pronounced for men. Phonatory function is therefore likely to be affected to a greater extent in men than in women as age increases. While a few studies have examined age-related laryngeal changes in phonatory function in men, these studies have generally focused solely on men. The present study was conducted to examine the effects of aging upon phonatory function in both men and women within a single experimental paradigm. The design of this study will allow for a direct comparison of the effects of age, sex, and intensity upon acoustic and aerodynamic measures. Incorporation of all these factors into a single study eliminates possible confounding factors such as methodological issues, sample composition, sample size, etc. that limit the extent to which separate studies on similar populations may be compared.

Hypotheses

Laryngeal aging results in a variety of changes in phonatory function. It is hypothesized that these changes in phonatory function will be reflected in acoustic and aerodynamic measures associated with voice production in a variety of speech tasks. These changes will also be associated with various perceptual qualities that enable listeners to identify the age of a speaker. The central null hypothesis for this study, therefore, is that acoustic, aerodynamic, and perceptual measures are not distinct between men and women as a function of age or intensity level.

Given that this study examined the effects of sex, age, and intensity upon three different types of vocal measures (acoustic, aerodynamic, and perceptual), specific null hypotheses were established according to the type of measure and the influential factor. These hypotheses are presented below:

<u>The Effect of Sex upon the Acoustic, Aerodynamic, and Perceptual Measures</u>

(1) Fundamental frequency and fundamental frequency standard deviation will not differ significantly between men and women.

(2) Amplitude-based glottal airflow measurements will not differ significantly between men and women.

(3) The voices of women will not be perceived as significantly more breathy than the voices of men.

<u>The Effect of Age Upon the Acoustic, Aerodynamic, and Perceptual Measures</u>

(1) Elderly men will not produce significantly higher fundamental frequency values compared to young men; elderly women will not produce significantly lower fundamental frequency values compared to young women.

(2) Fundamental frequency standard deviation values will not differ significantly between young and elderly speakers.

(3) Amplitude-based glottal airflow measurements will not differentiate elderly speakers from young speakers.

(4) The voices of elderly men will not be perceived as significantly more breathy than the voices of younger men; the voices of young women will not be perceived as significantly more breathy than the voices of elderly women.

<u>The Effect of Intensity Upon the Acoustic, Aerodynamic, and Perceptual Measures</u>

(1) The measurements of fundamental frequency, peak glottal airflow, alternating glottal airflow, and maximum flow declination rate will not increase with increased vocal intensity for both young and elderly speakers.

(2) The measurements of fundamental frequency standard deviation, minimum glottal airflow, and the ratio of minimum glottal airflow to peak glottal airflow will not decrease with increased vocal intensity for both young and elderly speakers.

(3) Increased vocal intensity will not affect the perception of breathiness in both young and elderly speakers.

(4) The perception of breathiness will not be significantly correlated with the physiological measures of minimum glottal airflow, maximum flow declination rate, and the ratio of minimum glottal flow to peak glottal airflow.

CHAPTER 2
MATERIALS AND METHODS

Subjects. Approval from the University of Florida Health Science Center Institutinal Review Board was obtained prior to enrolling subjects in the study. Subjects were recruited from volunteers at the University of Florida Health Science Center and the University of Florida, as well as residents of Gainesville, Florida, and Tallahassee, Florida. Informed consent was obtained from all subjects. The results of a power analysis indicated that a total of 112 subjects were required for this study (see Table 2-1). The power of the sample size was based on the data obtained for peak glottal airflow in Sapienza and Dutka's (1996) study, which demonstrated the greatest variability in peak airflow for the 70 year-old women compared to the younger age groups.

Table 2-1. Results of the power analysis, based on peak glottal airflow of women of different ages.

Mean, 20 year-old women	.267 l/s
Mean, 70 year-old women	.392 l/s
SD of 70 year-old women	.164 l/s
Significance level	.05
Power	.800

Equal sample size for both groups is calculated to be 28.025

(Sapienza & Dutka, 1996)

The 112 subjects were divided into four groups of 28 subjects, based on age and sex: Young men and women (20-30 years) and elderly men and women (65-75 years).

The younger age limit of 20 to 30 years was chosen as it represents the period prior to significant degeneration of the laryngeal structures (Kahane, 1987). The lower age limit for the elderly group was placed at 65 years as significant age-related anatomical changes have been observed by this age (Morrison et al., 1989; Pressman & Kelemann, 1955).

The lower age limit of 65 years for the elderly subjects was also selected to obtain a representative sample of healthy elderly individuals and to help insure that any observed changes were due to the normal aging process rather than the result of disease (Ramig & Ringel, 1983). Subjects were included based on the following documented criteria:

(1) Non-treatment seeking individuals who exhibited speech intelligibility and vocal quality within normal limits for age and sex as judged by a licensed, certified speech-language pathologist.

(2) Lack of symptoms of vocal abuse (i.e., hoarseness, fatigue, loudness disturbances, loss of range, breathiness, tickling or choking sensation, pain in throat, pitch breaks, phonation breaks).

(3) Negative history for excessive vocal usage, either in personal or professional life.

(4) Negative history for cognitive, psychological, respiratory, cardiovascular, and/or neurological disease, per subject report.

(5) Documented physical examination within the past 1-2 years.

(6) No symptoms of allergies, colds, or other illnesses on the day of testing.

(7) Nonsmokers for at least the past 10 years.

(8) No drug or alcohol abuse.

(9) Not pregnant.

(10) Premenopausal women not examined on days they were menstruating or experiencing symptoms of menstrual discomfort.

(11) Ambulatory and maintaining an independent household.

(12) Adequate cognitive and motoric abilities to participate in the experimental procedures.

Subjects were also included based on the results of specific screening tasks:

(1) Voice production within normal limits acoustically, as determined by the Kay Elemetrics *Multidimensional Voice Program* using the parameters of F_0, percent jitter, shimmer (dB), and noise-to-harmonic ratio (NHR).

(2) Hearing thresholds within normal range (25 dB HL at 0.5, 1.0, and 2.0 kHz) for subjects 20-30 years of age, and 40 dB HL at 1.0 kHz for subjects 65-75 years of age (Ventry & Weinstein, 1983).

(3) Normal vital capacity for age and sex.

(4) Body mass index within normal limits.

Procedure: Initial Screening. All subjects were initially screened by means of the *Multidimensional Voice Program (MDVP)*. *MDVP* is a software option for the *Computerized Speech Lab 5.X* (Kay Elemetrics). *MDVP* has been shown to be a reliable and valid system for acoustic measurement of the voice (Cimino & Sapienza, 1999; Kent, Vorperian, & Duffy, 1999; Natour, Cimino-Knight, Wingate, & Sapienza, in press). The measures chosen for the screening procedure to distinguish between normal and dysphonic voices (F_0, percent jitter, shimmer (dB), and NHR) have been shown to be reliable and valid distinguishing characteristics of normal versus dysphonic voices (Hirano, Tanaka, Fujita, & Teresawa, 1991; Ludlow, Bassich, Connor, Coulter, & Lee, 1987; Yumoto, Gould, & Baer, 1982; Yumoto, Sasaki, & Okamura, 1984).

Subjects were seated during the initial screening procedure. A head-worn cardioid condenser microphone (ATM75, Audio-Technica), angled 6 cm to the right of the subject's mouth, was used to record the voice sample (Titze & Winholtz, 1993). Subjects were instructed to sustain the vowel /ɑ/ at a comfortable pitch and loudness level for approximately 2 to 3 seconds. Occasionally, subjects were noted to change their

habitual pitch and loudness level during this task. In order to counteract this change, subjects were instructed to count to 5 in a normal voice and then sustain the vowel / / upon immediate completion of the counting. This counting task was successful in permitting the subjects to use their normal method of phonation for the sustained vowel task.

Upon completion of phonation, the subject's sustained vowel sample was immediately analyzed. Data concerning F_0, percent jitter, shimmer (dB), and NHR was obtained (see Figure 2-1). Subjects were included in the study only if they presented with a normal voice as judged by certified speech-language pathologist and as indicated by the results of this procedure.

All subjects also underwent a hearing screening, as detailed in the inclusion criteria above. Individuals who did not pass the hearing screening were not included in the study and were subsequently referred to an audiologist for further evaluation.

Following these screening tasks, a measure of forced vital capacity was obtained by means of a portable spirometer (MasterScreen-IOS, Erich Jaeger, GMBH, Germany) in order to determine if the subject's lung function was within normal limits. Subjects were instructed by the investigator to "take a deep breath from your stomach and blow out all your air as fast and hard as you can." The portable spirometer provided information concerning forced vital capacity and forced expiratory volume. It was also able to distinguish between individuals with normal, unrestricted airflow and those individuals with mild to severe restriction. Individuals who did not exhibit normal spirometry as indicated by normed reference values within the spirometer unit were not included in the study.

Sampled Data:	F.G.
Signal Level:	7204
Sampling Rate:	50000
Time Range:	0.00000 sec
	2.75000 sec

Average Fundamental Frequency	**Fo**	**=**	**110.686 Hz**
Average Pitch Period	To	=	9.035 ms
Highest Fundamental Frequency	Fhi	=	113.109 Hz
Lowest Fundamental Frequency	Flo	=	108.143 Hz
Standard Deviation of Fo	STD	=	0.973 Hz
Phonatory Fo-Range in semi-tones	PFR	=	2
Fo-Tremor Frequency	Fftr	=	1.216 Hz
Amplitude Tremor Frequency	Fatr	=	2.312 Hz
Length of Analyzed Sample	Tsam	=	2.750 s
Absolute Jitter	Jita	=	33.298 us
Jitter Percent	**Jitt**	**=**	**0.369 %**
Relative Average Perturbation	RAP	=	0.165 %
Pitch Perturbation Quotient	PPQ	=	0.231 %
Smoothed Pitch Perturb. Quotient	sPPQ	=	0.538 %
Fundamental Frequency Variation	vFo	=	0.879 %
Shimmer in dB	**ShdB**	**=**	**0.192 dB**
Shimmer Percent	Shim	=	2.216 %
Amplitude Perturbation Quotient	APQ	=	1.815 %
Smoothed Ampl. Perturb. Quotient	sAPQ	=	4.346%
Peak-Amplitude Variation	vAm	=	7.074 %
Noise to Harmonic Ratio	**NHR**	**=**	**0.0992**
Voice Turbulence Index	VTI	=	0.0390
Soft Phonation Index	SPI	=	10.7210
Fo-Tremor Intensity Index	FTRI	=	0.274 %
Amplitude Tremor Intensity Index	ATRI	=	3.420 %
Degree of Voice Breaks	DVB	=	0.000
Degree of Sub-Harmonics	DSH	=	0.000
Degree of Voiceless	DUV	=	0.000
Number of Voice Breaks	NVB	=	0
Number of Sub-Harmonic Segments	NSH	=	0
Number of Unvoiced Segments	NUV	=	0
Number of Segments Computed	SEG	=	87
Total Pitch Periods Detected	PER	=	303

Figure 2-1. Example of printout obtained from the MDVP program during production of the sustained vowel /   /.

Procedure: Aerodynamic Assessment. The aerodynamic procedure was completed using a circumferentially-vented respiratory face mask (Rothenberg, 1977) connected to a pressure transducer (PTW-1). The system was calibrated with a known airflow value (.500 l/s with a 2 liter volume exchange) from a rotameter (MCU-4 calibration unit, Glottal Enterprises) prior to each recording session (Sapienza & Dutka, 1996). Digital inverse filtering of the airflow signal was completed using *CSpeech 4.0* (Milenkovic, 1992) to yield a glottal airflow waveform (Rothenberg, 1973; 1977). All data was recorded and stored on a PCM Vetter data recorder (model 3000A) coupled to a customized VHS recorder.

Each subject was asked to prolong the vowel /ɑ/ three times for approximately 3 to 5 seconds at a comfortable effort level and natural pitch level while speaking into the circumferentially-vented face mask. Sound pressure levels (SPL) were monitored visually via an analog SPL monitor (FSPL-1, DFI Enterprises, Inc.) connected to the face mask. Subjects were instructed to maintain a steady SPL (± 1-2 dB) for all three trials. Most subjects were able to monitor their SPL independently using the visual monitor. Occasionally, however, some of the subjects in the older age range required assistance in monitoring SPL, due to visual difficulties (use of the mask prevented some subjects from wearing their eyeglasses, which hampered their ability to see the SPL monitor). Trials involving excessive SPL, defined as 2 dB greater than the SPL level exhibited during comfortable phonation, were not included for analysis.

Each subject was then asked to prolong the vowel /ɑ/ at 10 dB (± 1-2 dB) above their comfortable loudness level for approximately 3 to 5 seconds. This increased loudness task was conducted following the comfortable effort level task in order to avoid

any negative effects that increased vocal loudness may have had on comfortable, habitual voice production (i.e., fatigue and increased vocal loudness for the comfortable phonation task). Three trials also were obtained for this task, and SPL continued to be monitored via the analog SPL monitor in order to maintain a steady SPL level ($\pm$ 1-2 dB). As with the comfortable effort level task, some assistance in monitoring SPL was required for the older subjects. In order for all subjects to become familiar with phonating at a level approximately 10 dB above their comfortable effort level, a brief practice session was initiated prior to the actual recording of the increased loudness samples. Most subjects were able to learn to sustain the vowel /ɑ/ at this specified loudness level. Two subjects were unable to sustain the vowel /ɑ/ at a specific loudness level and were therefore not included in the study.

The data were checked following each recording attempt for possible air leaks from the face mask, as an air leak can affect the airflow measurements. Air leakage is generally indicated by negative minimum airflow values, or negative voltage as measured during online recording. Such trials were not included for analysis. In addition, a "mask off" condition, during which the face mask was removed from the subject's face, was used to allow for recalibration of the transducer's electronic offset from baseline to zero. This technique was used at the beginning of each recording attempt and between trials.

Several amplitude-based measurements were derived from the glottal airflow waveform. These measurements included: peak glottal airflow, minimum glottal airflow, alternating glottal airflow, maximum flow declination rate, and minimum glottal airflow/peak glottal airflow. These measures are described in detail below.

Peak glottal airflow: Peak flow refers to the amount of airflow from the zero flow baseline to maximum flow (Hertegard & Gauffin, 1991), i.e., the maximum rate of airflow during the vibratory cycle (Holmberg et al., 1988; 1989), and is associated with maximum vocal fold abduction. Normative values for young women range from .286 l/s (Holmberg, Hillman, Perkell, & Gress, 1994) to .470 l/s (Hertegard, Gauffin, & Karlsson, 1992). Normative values for young men range from .279 l/s to .410 l/s (Holmberg et al., 1994). Peak flow values of .392 l/s have been reported for 70 year-old women (Sapienza & Dutka, 1996). Higgins and Saxman (1993) reported data concerning a similar measurement in elderly men, termed flow amplitude rates (.330 l/s for men aged 69 years or greater). Peak flow is represented by point X on Figure 2-2.

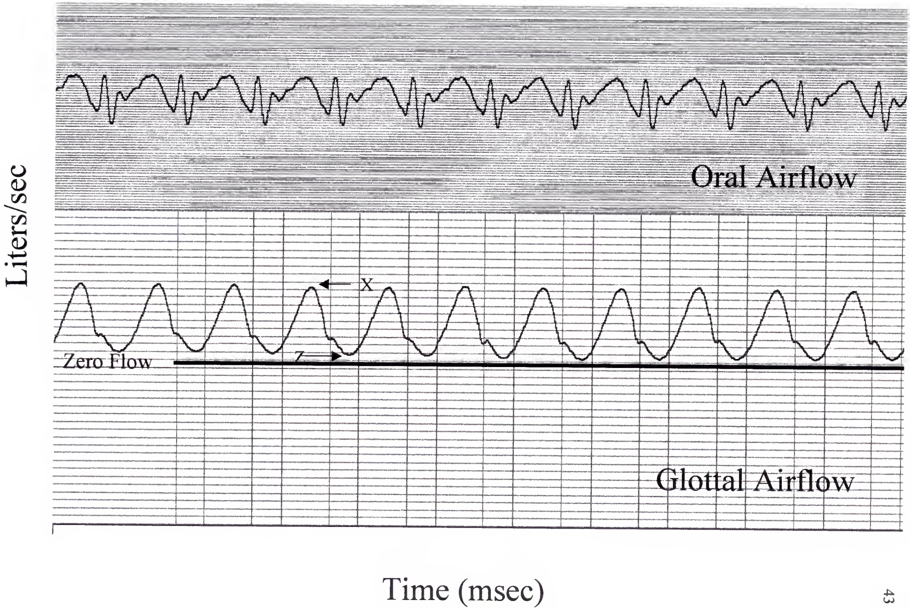
Minimum glottal airflow: The term "minimum flow" is used to refer to the amount of air that flows through the glottis during the closed phase of the vibratory cycle (Karlsson, 1988; Rothenberg, 1989) and theoretically should approach a value of "0" during glottal closure. However, several studies have shown that normal speakers frequently exhibit a small glottal leak. The small amount of flow observed during the closed phase of the vibratory cycle is thought to be due to vertical movements of the vocal folds (Hertegard & Gauffin, 1991; Sundberg, 2001). Minimum flow rates for young women range from .090 l/s to .130 (Hertegard & Gauffin, 1992; Perkell, Hillman, & Holmberg, 1994). Minimum flow rates for young men range from .050 to .120 l/s (Hertegard & Gauffin, 1992; Holmberg et al., 1989). Minimum flow rates range from .060 to .122 l/s have been reported for elderly women (69+ years old) (Higgins & Saxman, 1991; Sapienza & Dutka, 1996). Minimum flow rates of .060 l/s have been

reported for elderly men (Higgins & Saxman, 1991). Minimum flow is represented by point Z on Figure 2-2.

Alternating glottal airflow: Alternating (AC) flow is defined as peak flow minus minimum flow (Hertegard & Gauffin, 1991; Higgins & Saxman, 1991) and represents that airflow which is modulated by the vocal folds during voicing (see X-Z on Figure 2-2). It is viewed as an index of the magnitude of vocal fold oscillation. Alternating flow has been shown to be affected by both frequency (Holmberg et al., 1989) and intensity (Holmberg et al., 1988). Normative values for AC flow for young women range from .140 l/s (Holmberg et al., 1988) to .270 l/s (Sapienza & Dutka, 1996). For young men, AC flow values range from .260 l/s (Holmberg et al., 1988) to .370 l/s (Higgins & Saxman, 1991). AC flow rates of .170 to .270 l/s have been reported for elderly women (69+ years old) (Higgins & Saxman, 1991; Sapienza & Dutka, 1996). AC flow rates of .370 l/s have been reported for elderly men (Higgins & Saxman, 1991).

Maximum flow declination rate: Maximum flow declination rate (MFDR) is obtained by differentiating the glottal airflow signal. It is defined as "the maximum rate of decrease in airflow" and corresponds to the negative peak of the differentiated glottal airflow waveform (Gauffin & Sundberg, 1989). MFDR has been shown to increase with intensity (Gauffin & Sundberg, 1989; Holmberg et al., 1988, 1994) but not with frequency (Holmberg et al., 1989). Normative values for MFDR in young women range from 164 l/s/s to 184 l/s/s (Holmberg et al., 1988, 1989, 1994; Perkell et al., 1994). Normative values for MFDR in young men range from 279 l/s/s to 337 l/s/s (Holmberg et al., 1988; 1989; 1994). Data concerning MFDR in the voices of elderly men and women have not been reported.

Figure 2-2. Inverse-filtered glottal airflow waveform depicting peak glottal airflow, minimum glottal airflow, and maximum flow declination rate.


Liters/sec
Oral Airflow
X
Z
Zero Flow
Glottal Airflow
Time (msec)

Minimum glottal airflow/peak glottal airflow. The ratio of minimum glottal airflow to peak glottal airflow (DC/PK) represents the percentage of "wasted" airflow relative to the total airflow. This measure has been shown to correlate positively with the degree of breathiness (Fritzell, Hammarberg, Gauffin, Karlsson, & Sundberg, 1986; Hertegard & Gauffin, 1991). Sapienza and Dutka (1996) reported values for this measure ranging from 42% for the 20 year-old women to 33% for the 70 year-old women. Comparable data in men of any age have not been reported.

Procedure: Acoustic analysis. The acoustic analysis of each subject's voice included the following measurements: fundamental frequency, fundamental frequency standard deviation, and sound pressure level (SPL). Fundamental frequency (F_0) was included to observe changes in overall pitch level with age. Fundamental frequency standard deviation (F_0 SD) was included as an index of F_0 stability. Finally, SPL was included to assess the relative loudness levels of comfortable and loud phonation. The relative SPL was determined using the average root-mean-square (RMS) of the energy signal obtained from the vowel segment (*CSL,* Kay Elemetrics). All measures were obtained from the same sustained vowel samples used in the aerodynamic assessment task, at both a comfortable and increased effort level. Measures were derived from the airflow waveform obtained through digitization and inverse-filtering of the recorded signal via *CSpeech.*

Procedure: Perceptual analysis. A perceptual evaluation of the subject's recorded voice segments was completed. This task was included in order to determine if the age of the speaker differentially affects listener's perception of vocal quality, as well as the effect of loudness on vocal quality as a function of age and sex. In addition, the ratings obtained from the perceptual task were individually correlated with a number of the aerodynamic measurements previously described. To insure that listeners were focusing on vocal quality rather than articulatory or suprasegmental characteristics associated with connected speech, recordings of the sustained vowel / / obtained during the aerodynamic assessment were used. Use of whole vowel segments for perceptual ratings of breathiness has been shown to be as reliable as connected speech for perceptual ratings of breathiness, roughness, and severity (de Krom, 1994). The second trial for each task condition (comfortable and loud) was selected for each subject as a representative voice sample. An additional 10 trials were repeated for each condition for reliability purposes, resulting in a total of 244 samples (112 subjects x 2 trials) + 20 reliability trials = 244 samples).

All voice samples were digitized and edited using the software program *Cool Edit*. All samples were confined to a length of 3 to 5 seconds, digitized at 10,000 Hz., low-pass filtered at 4000 Hz., and saved as a waveform. The order of presentation of the samples was randomized using *MATLAB 5.0*, and the samples were subsequently presented to the listeners in a randomized order.

Five experienced speech-language pathologists served as listeners. Each listener had at least five years of clinical experience, with significant experience in assessing young and elderly adults with voice disorders. Years of experience ranged from 5 to 20

years. The use of experienced listeners is based on the findings of Kreiman, Gerratt, and Precoda (1990), who reported that naïve listeners paid little attention to the fine details of vocal quality. All listeners demonstrated pure tone thresholds of better than 20 dB HL, for both ears at the octave frequencies of 250 to 4000 Hz.

Listeners were asked to rate the perceived breathiness in each subject's voice. Breathiness was chosen as a distinguishing vocal quality as previous literature indicates that this is a prominent attribute in distinguishing the elderly voice from the young voice (Hartman & Danhauer, 1976; Ryan & Burk, 1974). In addition, breathiness has been significantly correlated to the DC/PK ratio in dysphonic speakers (Fritzell et al., 1986). Breathiness was also chosen as a prominent vocal quality in order to correlate listener perception of inadequate vocal fold closure to the physiological measures of minimum flow, MFDR, and DC/PK, all of which reflect the movement and status of vocal fold closure during phonation, respectively. The perception of breathiness was rated using the GRBAS scale (Hirano, 1981). The GRBAS scale uses a 4-point ordinal scale, with "0" representing "not present" and "4" representing "severe" (see Table 2-2). For the purposes of the study, the listeners were instructed to focus only on the "B" portion ("breathiness") of the scale.

Table 2-2. GRBAS scale.

Severity Ratings:	0 = Normal
	1 = Slight
	2 = Moderate
	3 = Extreme
Definitions of Components:	
G = Grade (degree of hoarseness or voice abnormality)	
R = Rough (perceptual impression of the irregularity of vocal fold vibration)	
B = Breathy (perceptual impression of the extent of air leakage through the glottis	
A = Asthenia (weakness or lack of power in the voice	
S = Strain (perceptual impression of vocal hyperfunction	

Experimental Design. This study was conducted as a repeated measures of parallel groups of 112 (28+28+28+28) subjects comparing men and women of two age groups and two loudness conditions. All measurements were completed by the investigator.

Data Collection and Analysis. For both the acoustic and aerodynamic measurements, all trials of the speech tasks were recorded on the Vetter PCM recorder on VHS videotape and stored for subsequent analysis. Analysis of the utterances was completed using the *CSpeech 4.0* software program (Milenkovic, 1992). For each trial of sustained vowel phonation, the middle 200 milliseconds of phonation were hand-marked for analysis. The mid-portion of the vowel segment was used for analysis in order to negate any onset/offset effects. Once all trials for each speech task were measured, mean and standard deviation values were obtained for each airflow measurement according to type of task.

Reliability. Inter-measurer and intra-measurer reliability was completed on 10% of the acoustic and aerodynamic data. Pearson r^2 correlation coefficient measures were high for intra-measurer reliability ranging from r^2 =.946 to r^2 = .998 for all measurements. Inter-measurer reliability was also high, with Pearson r correlation coefficients ranging from r^2 = .943 to r^2 = .998.

Intra-rater reliability of the five judges who participated in the perceptual task was low to high, ranging from r^2=.42 to r^2=.83 (see Table 2-3). Interestingly, experience did not seem to equate with intra-rater reliability. Inter-rater reliability was also low to moderate, ranging from r^2=.05 to r^2=.59 (see Tables 2-4 and 2-5).

Due to low inter-rater reliability, the individual ratings were not collapsed across listeners. Rather, the ratings of each listener were individually correlated with the measures of minimum flow, MFDR, and the ratio of minimum flow to peak flow.

Table 2-3. Number of years of experience of expert raters and intra-rater reliability.

Rater	Yrs. Exp.	r^2 (intra-rater)
R1	20	0.51
R2	17	0.72
R3	20	0.68
R4	9	0.42
R5	5	0.83

Table 2-4. Pearson (r^2) correlation coefficients for inter-rater reliability among the five expert judges in rating breathiness during sustained phonation at a comfortable intensity level. Level of significance is included in parentheses.

	R1	R2	R3	R4	R5
R1	1.000 (.000)	0.278 (.003)	0.300 (.001)	0.359 (.001)	0.277 (.003)
R2	0.278 (.003)	1.000 (.000)	0.544 (.000)	0.591 (.000)	0.483 (.000)
R3	0.300 (.001)	0.544 (.000)	1.000 (.000)	0.540 (.000)	0.444 (.000)
R4	0.359 (.000)	0.591 (.000)	0.540 (.000)	1.000 (.000)	0.488 (.000)
R5	0.277 (.003)	0.483 (.000)	0.444 (.000)	0.488 (.000)	1.000 (.000)

Table 2-5. Pearson (r^2) correlation coefficients for inter-rater reliability among the five expert judges in rating breathiness during sustained phonation at a loud intensity level. Level of significance is included in parentheses.

	R1	R2	R3	R4	R5
R1	1.000 (.000)	0.050 (.601)	0.109 (.254)	0.020 (.834)	0.353 (.000)
R2	0.050 (.601)	1.000 (.000)	0.207 (.028)	0.149 (.117)	0.483 (.292)
R3	0.109 (.254)	0.207 (.028)	1.000 (.000)	0.252 (.007)	0.281 (.003)
R4	0.241 (.010)	0.149 (.117)	0.252 (.007)	1.000 (.000)	0.336 (.000)
R5	0.353 (.000)	0.292 (.002)	0.281 (.003)	0.336 (.000)	1.000 (.000)

Statistical Analysis. An initial correlation analysis was also completed to determine if an analysis of covariance (ANCOVA) would be required. Individual SPL level was significantly correlated with a number of variables during comfortable phonation, and with AC flow and MFDR during loud phonation (see Table 2-6). An ANCOVA was therefore completed using SPL as the covariate.

Means and standard deviations for each subject according to task condition (comfortable and loud) were obtained using the individual means obtained from each trial. Overall group means and standard deviations for each group were calculated from the overall mean for each subject. Separate means and standard deviations were computed for each age group and sex according to type of task.

Split-plot ANCOVA's were used to examine group differences for each dependent variable, with individual SPL level included as a covariate. Between-subject factors included age (young vs. elderly) and sex (male vs. female). Vocal intensity was included as a within-subject repeated measures factor (comfortable vs. loud) for each dependent variable. The seven dependent variables included fundamental frequency, fundamental frequency standard deviation, peak glottal airflow, minimum glottal airflow, alternating glottal airflow, maximum flow declination rate, and the ratio of minimum airflow/peak airflow.

The probability level for all ANCOVA analyses was set *a priori* at the $p \leq 0.05$ level. Subsequent pairwise comparisons were conducted using the least significant difference (LSD) test (Ott, 1993). Statistical significance for the pairwise comparisons

(total = 48) was set at the Bonferroni corrected level of $p<.001$ [.05/48 = .001] (Maxwell & Satake, 1997).

Table 2-6. Significant Pearson r^2 correlations among the dependent variables according to phonation condition ($p \leq .05$).

Variable	Comfortable phonation	Loud phonation
SPL (comfortable)	Peak flow (.234)	
	DC flow (-.218)	
	AC flow (.347)	
	MFDR (-.756)	
	DC/PK (-.324)	
SPL (loud)		AC flow (.191)
		MFDR (-.371)
Peak flow (comfortable)	AC flow (.915)	Peak flow (.870)
	F_0 (.572)	DC flow (.442)
	F_0 SD (.442)	AC flow (.839)
		MFDR (.564)
		F_0 (.564)
		F_0 SD (.440)
Peak flow (loud)	Peak flow (.870)	DC flow (.454)
	AC flow (.839)	AC flow (.977)
	MFDR (-.502)	MFDR (.-753)
	F_0 (-.622)	F_0 (-.600)
	F_0 SD (-.474)	F_0 SD (-.495)
DC flow (comfortable)	DC/PK (.784)	DC flow (.673)
		DC/PK (.522)
DC flow (loud)	Peak flow (.442)	Peak flow (.454)
	DC flow (.673)	DC/PK (.748)
	DC/PK (.494)	
AC flow (comfortable)	Peak flow (.915)	Peak flow (.839)
	MFDR (-.541)	AC flow (.866)
	DC/PK (-.494)	MFDR (-.633)
	F_0 (-.667)	F_0 (-.659)
		F_0 SD (-.571)
AC flow (loud)	Peak flow (.839)	Peak flow (.977)
	AC flow (.866)	MFDR (-.789)
	MFDR (-.541)	F_0 (-.643)
	F_0 (-.666)	F_0 SD (-.560)
	F_0 SD (-.553)	

Table 2-6. Continued.

Variable	Comfortable phonation	Loud phonation
MFDR (comfortable)	SPL (-.756)	Peak flow (.-502)
	AC flow (.-541)	AC flow (-.541)
		MFDR (.669)
MFDR (loud)	Peak flow (-.564)	Peak flow (-.753)
	AC flow (-.633)	AC flow (-.789)
	MFDR (.669)	
	F_0 (.403)	
	F_0 SD (.420)	
DC/PK (comfortable)	DC flow (.784)	DC flow (.494)
	AC flow (-.494)	DC/PK (.651)
	F_0 (.477)	F_0 (.467)
	F_0 SD (.560)	F_0 SD (.517)
DC/PK (loud)	DC flow (.522)	DC flow (.748)
	DC/PK (.651)	F_0 SD (.408)
	F_0 SD (.507)	
F_0 (comfortable)	Peak flow (.572)	Peak flow (-.622)
	AC flow (-.667)	AC flow (-.643)
	DC/PK (.477)	MFDR (.403)
	F_0 SD (.842)	F_0 (.961)
		F_0 SD (.865)
F_0 (loud)	Peak flow (.564)	Peak flow (-.600)
	AC flow (-.659)	F_0 SD (.883)
	DC/PK (.467)	
	F_0 (.961)	
	F_0 SD (.803)	
F_0 SD (comfortable)	Peak flow (.442)	Peak flow (-.622)
	DC/PK (.560)	AC flow (-.553)
	F_0 (.842)	MFDR (.420)
		DC/PK (.507)
		F_0 (.803)
		F_0 SD (.847)
F_0 SD (loud)	Peak flow (.440)	Peak flow (-.495)
	AC flow (-.571)	AC flow (-.560)
	DC/PK (.517)	DC/PK (.408)
	F_0 (.865)	F_0 (.883)
	F_0 SD (.847)	

CHAPTER 3
RESULTS

This aim of this was study was to examine the effects of aging upon phonation as reflected in specific aerodynamic and acoustic measurements. A second purpose was to examine the interaction between age, sex, vocal intensity, and the acoustic and aerodynamic measurements of phonation. A third goal was to examine the relationship between selected physiologic measurements of vocal fold function and listener perception of breathiness in healthy young and elderly adults.

This study involved three independent variables: age, sex, and intensity. Eight dependent variables were included for analysis: fundamental frequency (F_0), fundamental frequency standard deviation (F_0 SD), sound pressure level (SPL), peak glottal airflow, minimum glottal airflow, alternating glottal airflow (AC flow), maximum flow declination rate (MFDR), and the ratio of minimum glottal airflow/peak glottal airflow (DC/PK).

Acoustic and Aerodynamic Measurements

Main Effects

Tables 3-1 and 3-2 present the adjusted means and standard deviations from the ANCOVA for the dependent variables for all subject groups according to loudness condition. Table 3-3 presents the results of the ANCOVA for the acoustic and

aerodynamic measures. Tables 3-4 through 3-6 present the results of post-hoc analyses completed for the pairwise comparisons using the LSD test.

The results of the ANCOVA revealed a significant main effect of age for peak glottal airflow and AC flow ($F=25.599$, $p \leq .000$). Both peak and AC flow increased as a function of age (see Tables 3-1 and 3-2). Significant main effects of age were also found for F_0 and MFDR but were disregarded due to the interaction of sex x age for these variables.

The results of the ANCOVA revealed a significant main effect of age for peak glottal airflow and AC flow ($F=25.599$, $p \leq .000$). Both peak and AC flow increased as a function of age (see Tables 3-1 and 3-2). Significant main effects of age were also found for F_0 and MFDR but were disregarded due to the interaction of sex x age for these variables.

Table 3-1. Overall adjusted means and standard deviation values of the acoustic and aerodynamic measurements obtained during comfortable phonation.

	F_0	F_0 SD	Peak	DC	AC	MFDR	DC/PK
yw x	224.63	3.44	0.08	0.03	0.05	-88.83	37.70
yw sd	21.48	0.14	0.02	0.02	0.01	33.33	11.35
ew x	189.57	2.95	0.10	0.03	0.07	-101.54	24.84
ew sd	33.98	0.12	0.03	0.02	0.02	49.01	14.10
ym x	107.19	1.19	0.14	0.02	0.12	-136.21	16.26
ym sd	13.65	0.13	0.04	0.01	0.03	70.07	9.30
em x	115.50	1.66	0.16	0.03	0.13	-125.11	19.94
em sd	23.33	0.12	0.06	0.02	0.03	57.38	9.65

F_0 = fundamental frequency (Hz); F_0 SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow x 100 = %.
Other abbreviations: yw = young women; ym = young men; ew = elderly women, em = elderly men.

Table 3-2. Overall adjusted means and standard deviation values of the acoustic and aerodynamic measurements obtained during loud phonation.

	F_0	F_0 SD	Peak	DC	AC	MFDR	DC/PK
yw x	257.32	3.51	0.09	0.02	0.07	-165.19	20.78
yw se	20.95	0.14	0.02	0.02	0.01	24.69	12.38
ew x	219.62	3.12	0.10	0.02	0.08	-147.85	17.83
ew sd	32.93	0.12	0.03	0.02	0.03	41.37	15.07
ym x	123.80	1.14	0.19	0.02	0.17	-255.38	9.61
ym sd	13.58	0.12	0.04	0.01	0.04	69.47	6.35
em x	132.88	1.57	0.21	0.03	0.18	-221.99	13.80
em sd	21.70	0.12	0.06	0.02	0.05	60.71	6.28

F_0 = fundamental frequency (Hz); F_0 SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow x 100 = %.
Other abbreviations: yw = young women; ym = young men; ew = elderly women, em = elderly men

The results of the ANCOVA also revealed a significant main effect of sex for F_0, F_0 SD, peak glottal airflow, AC flow, MFDR, and DC/PK. These main effects were also disregarded as these measures demonstrated significant interactions of sex x age, sex x intensity, and/or a sex x age x intensity interaction (see Table 3-3).

Table 3-3. Results of ANCOVA on the seven dependent variables.

	Sex		Age		Intensity		Sex x Age		Sex x Intensity		Age x Intensity		Sex x Age x Intensity	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Fundamental Frequency	4426.221	0.000*	79.225	0.000*	5.444	0.022*	213.731	0.000*	17.367	0.000*	0.382	0.538	0.007	0.932
Fundamental Frequency standard deviation	761.667	0.000*	0.000	0.996	0.025	0.874	43.613	0.001*	1.999	0.160	0.048	0.828	0.245	0.622
Peak glottal airflow	761.163	0.000*	25.599	0.000*	0.102	0.750	2.219	0.139	51.197	0.000*	0.109	0.742	0.002	0.962
Minimum glottal airflow	0.974	0.326	3.400	0.068	0.287	0.593	31.228	0.000*	3.979	0.049	0.287	0.593	0.392	0.532
Alternating glottal airflow	871.052	0.000*	22.453	0.000*	0.580	0.448	0.799	0.373	48.355	0.000*	0.000	0.984	0.036	0.849
Maximum flow declination rate	184.567	0.000*	6.639	0.011*	1.200	0.276	5.059	0.027*	35.503	0.000*	1.823	0.180	0.412	0.522
Minimum glottal airflow/peak glottal airflow	98.038	0.000*	3.903	0.051	2.686	0.104	31.208	0.000*	5.467	0.000*	2.481	0.118	4.801	0.031*

* indicates significant at p <.05.

Table 3-4. Results of post hoc comparisons using the least significant difference test for the sex x age interaction, conducted at the Bonferroni corrected alpha level of $p \leq .001$. Significant results indicated by (*).

Variable	Contrast	Mean Difference	Standard Error	p
F_0	yw vs. ew	36.082	5.604	0.000*
	ym vs. em	8.874	5.604	0.116
	yw vs. ym	124.801	5.605	0.000*
	ew vs. em	79.845	5.604	0.000*
F_0 SD	yw vs. ew	0.445	0.197	0.026
	ym vs. em	0.445	0.197	0.026
	yw vs. ym	71.169	8.986	0.000*
	ew vs. em	51.030	8.985	0.000*
DC flow	yw vs. ew	0.001	0.004	0.227
	ym vs. em	0.001	0.004	0.019
	yw vs. ym	0.001	0.004	0.136
	ew vs. em	0.001	0.004	0.038
MFDR	yw vs. ew	1.265	8.984	0.888
	ym vs. em	21.404	8.984	0.019
	yw vs. ym	71.169	8.986	0.000*
	ew vs. em	51.030	8.985	0.000*

Abbreviations: yw=young women; ym=young men; ew=elderly women; em=elderly men

Table 3-5. Results of post hoc comparisons using the least significant difference test for the sex x intensity interaction, conducted at the Bonferroni corrected alpha level of $p \leq .001$. Significant results indicated by (*).

Variable	Contrast	Mean Difference	Standard Error	p
Fo	w-cf vs. w-ld	15.813	4.451	0.001*
	m-cf vs. m-ld	2.896	4.14	0.486
	w-cf vs. m-cf	96.118	2.179	0.000*
	w-ld vs. m-ld	109.034	2.193	0.000*
Peak flow	w-cf vs. w-ld	0.002	0.009	0.030
	m-cf vs. m-ld	0.003	0.008	0.003
	w-cf vs. m-cf	0.006	0.004	0.000*
	w-ld vs. m-ld	0.107	0.004	0.000*

Abbreviations: w=women; m=men; cf=comfortable phonation; ld=loud phonation

Table 3-5. Continued.

DC flow	w-cf vs. w-ld	0.001	0.004	0.242
	m-cf vs. m-ld	0.001	0.004	0.820
	w-cf vs. m-cf	0.001	0.002	0.473
	w-ld vs. m-ld	0.001	0.002	0.038
AC flow	w-cf vs. w-ld	0.002	0.008	0.086
	m-cf vs. m-ld	0.003	0.008	0.001*
	w-cf vs. m-cf	0.006	0.004	0.000*
	w-ld vs. m-ld	0.103	0.004	0.000*
MFDR	w-cf vs. w-ld	14.028	12.897	0.279
	m-cf vs. m-ld	39.483	11.995	0.001*
	w-cf vs. m-cf	33.937	6.312	0.000*
	w-ld vs. m-ld	87.448	6.356	0.000*

Abbreviations: w=women; m=men; cf=comfortable phonation; ld=loud phonation

Table 3-6. Results of post hoc comparisons using the least significant difference test for the sex x age x intensity interaction, conducted at the Bonferroni corrected alpha level of $p \leq .001$. Significant results indicated by (*).

Variable	Contrast	Mean Difference	Standard Error	p
DC/PK	yw-cf vs. yw-ld	0.102	0.034	0.004
	ew-cf. vs. ew-ld	0.003	0.028	0.342
	ym-cf vs. ym-ld	0.001	0.03	0.672
	em-cf vs. em-ld	0.002	0.029	0.401
	yw-cf vs. ew-cf	0.001	0.006	0.120
	yw-ld vs. ew-ld	0.001	0.006	0.055
	ym-cf vs. em-cf	0.002	0.006	0.002
	ym-ld vs. em-ld	0.002	0.006	0.017
	yw-cf vs. ym-cf	0.006	0.006	0.000*
	yw-ld vs. ym-ld	0.102	0.006	0.000*
	ew-cf vs. em-cf	0.007	0.006	0.000*
	ew-ld vs. em-ld	0.111	0.006	0.000*

Abbreviations: yw=young women; ym=young men; ew=elderly women; em=elderly men; cf=comfortable phonation; ld=loud phonation.

Interactions and Post-Hoc Tests

Sex x Age

Fundamental Frequency: As illustrated in Figure 3-1, women produced a higher mean F_0 than men. Post hoc analyses revealed that the young women exhibited a significantly higher F_0 than the young men ($p \leq .000$) and the elderly women ($p \leq .000$). The elderly women also exhibited a significantly higher F_0 compared to the elderly men ($p \leq .000$) but a significantly lower F_0 compared to young women ($p \leq .000$). There was a trend for F_0 to increase with age for men but the difference was not significant ($p=.116$) (see Table 3-4).

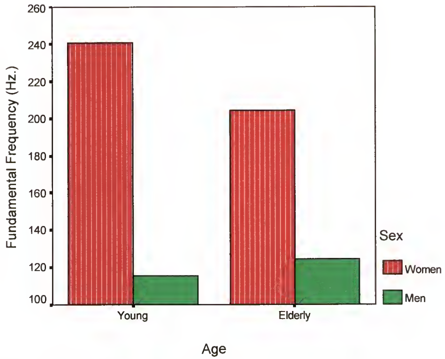


Figure 3-1. Sex x age interaction collapsed over intensity level for fundamental frequency.

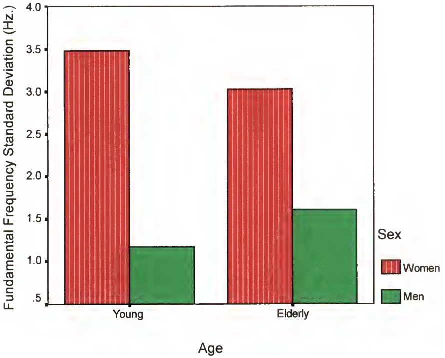


Figure 3-2. Sex x age interaction collapsed over intensity level for fundamental frequency standard deviation.

Fundamental frequency standard deviation: Women demonstrated greater F_0 SD values compared to men. F_0 SD decreased with age for women but increased for men (see Figure 3-2). Post hoc analyses revealed no significant difference between the young and elderly women ($p=.026$) or between the young and elderly men ($p=.026$), once corrected with the Bonferroni correction factor (see Table 3-4). However, F_0 SD was significantly greater for the young women compared to the young men ($p \leq .000$) and for the elderly women compared to the elderly men ($p \leq .000$).

In order to rule out any dependence of F_0 deviation on mean F_0 (Baken, 2000; Deal & Emmanuel, 1978), the F_0 SD values were converted into semitone standard deviation (STSD) (Dromey & Ramig, 1998a, b) using the following formula:

$$STSD = (12/\log 2) \times \log(x + SD/x - SD)$$

where x is the mean F_0 and SD is the standard deviation of F_0 in Hz. The STSD data are presented in Table 3-7. Subsequent analysis using paired samples t-test revealed significantly greater STSD for the young women compared to the young men ($t=5.605$, $p\leq.000$) but not for the elderly women compared to the elderly men ($t=2.439$, $p=.018$), once corrected with the Bonferroni correction factor.

Table 3-7. Semitone standard deviation data for young and elderly men and women grouped across intensity conditions.

Group	STSD
Young Women	0.493
Young Men	0.354
Elderly Women	0.501
Elderly Men	0.451

Minimum glottal airflow: As illustrated in Figure 3-3, minimum flow rates declined with age for women but increased with age for men. Additionally, young women exhibited higher minimum flow rates compared to young men and elderly women but lower than that of the elderly men. Post hoc analyses revealed that the age-related decrease in minimum flow rates for women was not significant ($p=.227$). The age-related increase in men was also not significant ($p=.019$) once adjusted with the Bonferroni correction factor. Similarly, there was no significant difference between the young women and young men ($p=.136$) or between the elderly women and elderly men ($p=.038$) when adjusted with the Bonferroni correction factor (see Table 3-4).

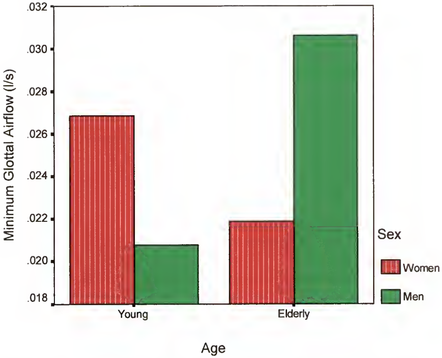


Figure 3-3. Sex x age interaction collapsed over intensity level for minimum flow.

<u>Maximum flow declination rate</u>. Men consistently produced higher MFDR values compared to women. As illustrated in Figure 3-4, MFDR values decreased with advancing age for men but minimally so for women. Post hoc analyses revealed no significant difference in MFDR between young and elderly women (p=.888) or between young and elderly men (p=.019) when adjusted with the Bonferroni correction factor. However, MFDR values were significantly greater for young men compared to young women ($p \leq .000$) and for elderly men compared to elderly women ($p \leq .000$) (see Table 3-4).

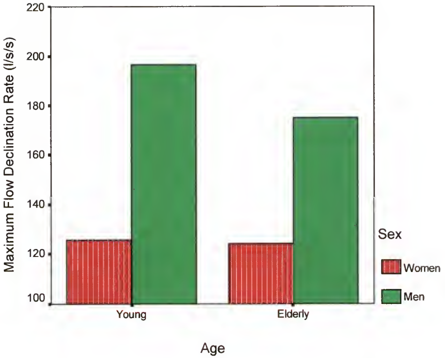


Figure 3-4. Sex x age interaction collapsed over intensity level for maximum flow declination rate.

Sex x Intensity

Fundamental Frequency: The women demonstrated higher mean F_0 values than their male counterparts during both intensity conditions (see Figure 3-5). F_0 increased for both men and women as a function of phonation condition (comfortable vs. loud). Post hoc analyses revealed that F_0 increased significantly for women with increased intensity ($p=.001$) but not for men ($p=.486$). Post hoc analyses also revealed that women generated a significantly higher F_0 compared to men during both comfortable ($p\leq.000$) and loud phonation ($p\leq.000$) (see Table 3-5).

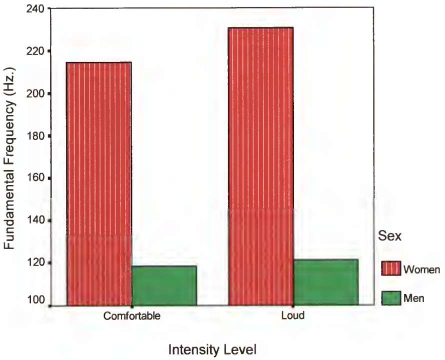


Figure 3-5. Sex x intensity interaction collapsed over age for fundamental frequency.

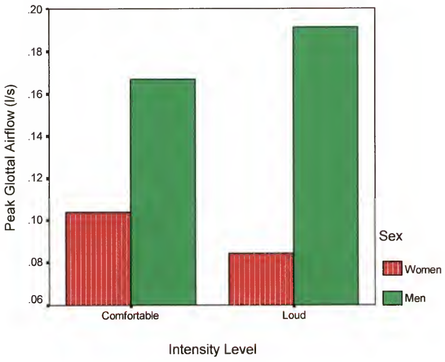


Figure 3-6. Sex x intensity interaction collapsed over age for peak glottal airflow.

Peak glottal airflow: Peak flow rates were higher for men compared to the women during both phonation conditions. Additionally, peak flow rates increased with increased intensity for the men while the women demonstrated a decline in peak flow rates with increased intensity (see Figure 3-6). Post hoc analyses revealed that the increase in peak flow from comfortable to loud phonation for men was not significantly different ($p=.030$) when adjusted with the Bonferroni correction factor. Similarly, the decrease in peak flow from comfortable to loud phonation for women was not significantly different ($p=.003$) when adjusted with the Bonferroni correction factor. However, men consistently demonstrated higher peak flow rates compared to women during both comfortable ($p \leq .000$) and loud ($p \leq .000$) phonation (see Table 3-5).

Minimum glottal airflow: As shown in Figure 3-7, women exhibited reduced minimum flow rates with increased intensity, while men demonstrated an increase. Post hoc analyses revealed no significant difference in minimum flow rates for either women ($p=.242$) or men ($p=.820$) with increased intensity. Additionally, there was no significant difference in minimum flow rates between men and women during comfortable phonation ($p=.473$) or loud phonation ($p=.038$) when adjusted with the Bonferroni correction factor (see Table 3-5).

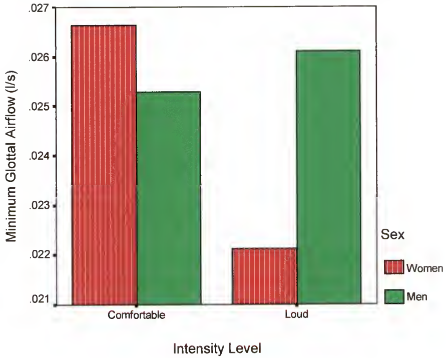


Figure 3-7. Sex x intensity interaction collapsed over age for minimum airflow.

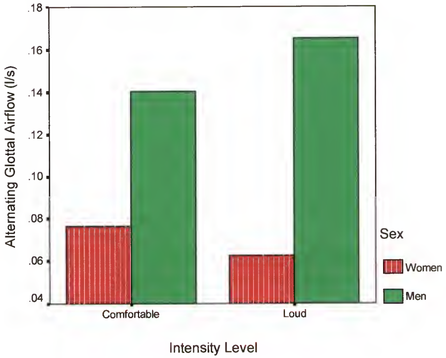


Figure 3-8. Sex x intensity interaction collapsed over age for alternating flow.

Alternating glottal airflow: Higher AC flow rates were observed for men compared to women within each intensity condition. AC flow rates increased with increased intensity for men but decreased for women (see Figure 3-8). Post hoc analyses revealed no significant decrease in AC flow rates for women from comfortable to loud phonation ($p=.086$) but a significant increase for men ($p=.001$). Additionally, men consistently generated higher AC flow rates than women during both comfortable ($p\leq.000$) and loud ($p\leq.000$) phonation (see Table 3-5).

Maximum flow declination rate: Figure 3-9 illustrates the results of the sex x intensity interaction for MFDR. For the female speakers, a decrease in MFDR was observed with increased intensity. In contrast, the male speakers demonstrated a marked increase in MFDR. Post hoc analyses revealed no significant change in MFDR from comfortable to loud phonation for women ($p=.279$). However, a significant increase in MFDR for men was found with increased intensity ($p=.001$). Additionally, men consistently generated significantly higher MFDR values than women during both comfortable ($p\leq.000$) and loud ($p\leq.000$) phonation (see Table 3-5).

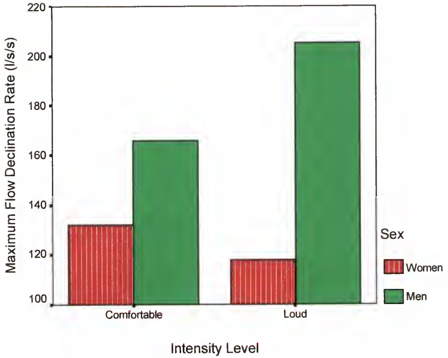
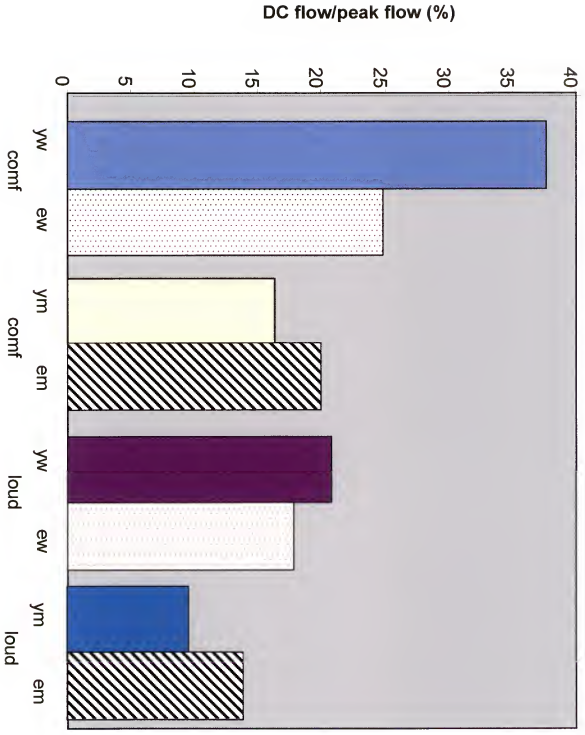


Figure 3-9. Sex x intensity interaction collapsed over age for maximum flow declination rate.

Sex x Age x Intensity

Minimum flow/Peak airflow ratio: As shown in Figure 3-10, DC/PK ratios increased with age for both groups of male speakers but decreased for the female speakers. All groups demonstrated a decrease in DC/PK with increased intensity. Post hoc analyses revealed that the difference in DC/PK between comfortable and loud phonation was not significantly different for either young women (p=.004) when adjusted with the Bonferroni correction factor, or for the elderly women (p=.342). Similarly, the decrease in DC/PK with increased vocal intensity was not significant for either young men (p=.672) or elderly men (p=.401) (see Table 3-6).

Figure 3-10. Sex x age x intensity interaction for DC/PK ratio.


DC flow/peak flow (%)
0
5
10
15
20
25
30
35
40
yw
ew
comf
ym
em
comf
yw
ew
loud
ym
em
loud

Further statistical analysis of comparisons revealed no significant difference between young and elderly women in DC/PK values during comfortable ($p=.120$) or loud ($p=.055$) phonation. Similarly, DC/PK values were not significantly different between the young and elderly men during comfortable ($p=.002$) or loud phonation ($p=.017$) once adjusted with the Bonferroni correction factor (see Table 3-6).

Significant differences were found between men and women of both age groups. Young women demonstrated significantly higher DC/PK values compared to young men during both comfortable ($p\leq.000$) and loud ($p\leq.000$) phonation. Likewise, elderly women demonstrated significantly higher DC/PK values compared to elderly men during both comfortable ($p\leq.000$) and loud ($p\leq.000$) phonation (see Table 3-6).

Perceptual Results

Listener Perception of Breathiness. Despite the low inter-rater reliability among the judges on specific ratings, there was general agreement among the raters in the perception of increased breathiness in the voices of the elderly speakers. Additionally, the perception of breathiness tended to decrease from comfortable to loud phonation. Table 3-6 presents the average ratings for all participant groups across intensity conditions. In comparing males to females, however, there were some discrepancies among the raters. Raters #2 and #4 tended to rate men as being more breathy than the women, within their respective age groups. This pattern was true for both comfortable and loud phonation, with the exception of loud phonation for rater #2 (see Table 3-8).

Correlation of perceptual ratings with airflow measures. Due to the relatively low correlation coefficients of intra-rater reliability for the five judges under both comfortable and loud phonation, it was difficult to examine which physiological measures were most

closely correlated to the rating of breathiness. Averaging of the rating scores was not completed due to low listener agreement concerning the breathiness ratings. Rather, the ratings of the judges were individually correlated with selected physiological measures. The measure of minimum flow was chosen as it is used as a typical index of vocal fold closure during the closed phase of phonation, and should therefore increase with increased vocal breathiness (Hertegard & Gauffin, 1991). The measure of MFDR was included as it serves as an index of the speed of vocal fold closure, and hence a reduction in MFDR would be associated with increased vocal breathiness (Holmberg et al., 1988). Finally, the measure of DC/PK was chosen as this measure has been previously shown to significantly correlate with pathological breathiness (Fritzell et al., 1986; Hertegard & Gauffin, 1991). As shown in Table 3-9, Pearson r^2 correlation coefficients were low to moderate for all measures across conditions and judges.

Table 3-8. Summed ratings of breathiness for the subject groups according to rater and phonation condition. A higher number indicates increased breathiness.

Subject group	Rater	Comfortable Phonation	Loud Phonation
Young women	R1	1.57	1.36
	R2	0.32	0.04
	R3	2.07	1.54
	R4	0.86	0.11
	R5	0.82	0.21
Young men	R1	1.36	1.46
	R2	0.43	0.11
	R3	2.00	1.89
	R4	0.96	0.29
	R5	0.50	0.21
Elderly women	R1	1.75	1.29
	R2	0.68	0.25
	R3	2.18	1.68
	R4	1.11	0.25
	R5	0.79	0.29
Elderly men	R1	1.64	1.47
	R2	0.79	0.21
	R3	2.11	1.68
	R4	1.25	0.68
	R5	0.82	0.21

Table 3-9. Pearson r^2 correlation coefficients demonstrating the relationship between physiologic measures and individual listener ratings. Level of significance is included in parentheses.

Rater	**DC flow (comf.)**	**DC flow (loud)**	**MFDR (comf.)**	**MFDR (loud)**	**DC/PK (comf.)**	**DC/PK (loud)**
R1	0.159 (.095)	0.184 (.052)	0.164 (.084)	-0.058 (.543)	0.096 (.316)	0.121 (.205)
R2	0.140 (.141)	0.100 (.292)	0.340 (.000)*	-0.030 (.757)	0.024 (.800)	0.007 (.945)
R3	0.179 (.059)	0.232 (.014)*	0.256 (.006)*	0.012 (.896)	0.069 (.470)	0.168 (.077)
R4	0.037 (.701)	0.179 (.059)	0.261 (.006)*	0.097 (.311)	-0.051 (.593)	0.053 (.582)
R5	0.107 (.260)	0.153 (.108)	0.423 (.000)	0.185 (.051)	0.112 (.240)	0.228 (.015)*

* Denotes a significant correlation at $p<.05$. DC flow = minimum glottal airflow; MFDR = maximum flow declination rate; DC/PK = the ratio of minimum glottal airflow to peak glottal airflow.

CHAPTER 4
DISCUSSION

The purpose of this investigation was to examine the effect of chronological aging and sex upon specific acoustic and aerodynamic measurements. A secondary goal was to examine the manner in which intensity changes affected these measurements. Finally, a third goal was to determine if any of the measurements correlated with breathiness, a perceptual voice quality often attributed to speakers of advanced age. The significance of the previously reported findings will now be discussed.

Acoustic and Aerodynamic Measures

The Effect of Age and Sex Upon the Acoustic Measurements

For the acoustic measures related to age, it was hypothesized that elderly males would produce a higher fundamental frequency (F_0) compared to the young men, while the elderly women would exhibit a reduction in F_0 compared to the young women. Additionally, it was predicted that elderly speakers, regardless of sex, would produce increased fundamental frequency standard deviation (F_0 SD) values compared to the groups of young speakers. For the acoustic measurements related to sex, it was hypothesized that men, regardless of age, would produce lower F_0 SD values than women.

Fundamental Frequency: F_0 values for the 20-30 year old women ranged from 178 Hz. to 292 Hz. with a mean of 233 Hz. These values are consistent with previously reported data for women of comparable ages (Higgins & Saxman, 1991). The men aged 20-30 years exhibited a mean F_0 of 114 Hz. (range of 79-145 Hz.), which is slightly lower than the average value reported in earlier studies (e.g., Higgins & Saxman, 1991; Higgins, Netsell, & Schulte, 1994; Shipp, Qi, Huntley, & Hollien, 1992). Examination of the data reveals that a large proportion of the young male speakers phonated at or below 100 Hz., which may have contributed to the lowered mean F_0 for these subjects.

Mean F_0 values for the male speakers were significantly lower compared to the female speakers, regardless of age. A lower F_0 occurs in adult male speakers due to the relatively larger membranous vocal fold length and overall increased size of the laryngeal structures (Titze, 1989).

Mean F_0 values for the elderly women differed significantly from those found for their younger counterparts. Elderly women demonstrated a mean F_0 of 196 Hz. (range of 142-315 Hz.) during comfortable phonation. The elderly women's mean F_0 was significantly lower than the F_0 of 224 Hz. found for the young women, and was consistent with previously reported literature (Awan & Mueller, 1992; Benjamin, 1981; McGlone & Hollien, 1969). The reduction in F_0 for elderly women is thought to be due to lowering of the larynx (Kahane, 1980), as well as post-menopausal hormonal changes. These hormonal changes result in vocal fold edema and thickening of the laryngeal mucosa (Abitbol, Abitbol, & Abitbol, 1999; Honjo & Isshiki, 1980).

Objective and subjective documentation of vocal changes have been reported in women after menopause. Boulet and Oddens (1996) reported that 29% of professional

female singers aged 40-64 years reported significant voice changes during or after menopause, including hoarseness, huskiness, lowering of pitch, increased instability of the voice, and difficulty achieving high musical notes. A number of studies have objectively supported the perception of reduced F_0 in elderly women (Brown et al., 1991; Lindholm, Vilkman, Raudaskoski, Suvanto-Luukkonen, & Kauppila, 1997; Murry, Brown, & Morris, 1995; Russell et al., 1995). Videostroboscopic data has demonstrated reduced vibratory amplitude and a decrease in mucosal wave for elderly women (Biever & Bless, 1989). Biever and Bless suggested that these changes may result from vocal fold edema and/or drying and thinning of the laryngeal mucosa, both of which may occur in response to menopausally-related endocrine changes. Thinning and drying of the laryngeal mucosa would increase the stiffness of the mucosal cover, resulting in reduced amplitude of vibration (Gracco & Kahane, 1989). Additionally, edema of the vocal folds would not only increase the effective mass of the vocal folds (thus contributing to a slower rate of vibration and subsequent lowering of F_0), but also restrict the movement of the mucosal cover leading to decreased vibratory amplitude.

In contrast, the elderly men demonstrated a slight but nonsignificant increase in F_0 compared to the younger men. The elderly men in the present study produced a mean F_0 of 123 Hz. (range of 73 -188 Hz), which is similar to that reported in earlier studies (Mysak, 1959; Orlikoff, 1990; Ramig & Ringel, 1983). Although a number of studies have reported a significant increase in F_0 for elderly men in comparison to young men (i.e., Honjo & Isshiki, 1980; Mysak, 1959), several other studies have shown no effect of age upon F_0 (Ramig & Ringel, 1983; McGlone & Hollien, 1969; Wilcox & Horii, 1980).

Interestingly, Orlikoff (1990) also reported increased F_0 values among elderly men but no statistical significance when compared to younger men.

One possible reason for these conflicting results may be due to differences in physiological aging. As noted by Ramig and colleagues in their review on vocal aging, "the progression of aging may differ across individuals of the same chronological age [and]....certain individuals may age more 'successfully' than the norm" (Ramig, Gray, Baker, Corbin-Lewis, Buder, Luschei, Coon, & Smith, 2001, p. 253). Hence, it is conceivable that different groups of elderly individuals may demonstrate differences in the extent to which aging affects voice production, even if effort is made to insure that all individuals are in good physical condition and health (Ramig & Ringel, 1983). This difference in physiological aging among similar individuals may account for the differing results observed in studies examining F_0 in elderly male speakers.

Fundamental Frequency Standard Deviation: F_0 SD was significantly greater for women compared to men, regardless of age. Following conversion of the F_0 SD data to STSD to eliminate the influence of mean F_0 upon the SD data, however, only the young women were significantly different from the young men. The difference in STSD between the elderly men and women were not significant. These results agree in part with data reported by Decoster & Debruyne (1997), who reported reduced F_0 SD for young men (20-29 years of age) and "young-old" men (60-69 years of age) compared to women of similar ages, but found increased F_0 SD for men 70 years of age and older compared to women in that age group.

One possible reason for the increased F_0 SD/STSD of the young women compared to male speakers may have been due to hormonal influences upon vocal fold

vibration. It is well known that the typical voice pattern fluctuates during a woman's 28-day menstrual cycle. Premenstrually-related vocal changes in trained singers include vocal fatigue, decreased intensity range, loss of harmonics, and reduced frequency perturbation (Abitbol, Brux, Millot, Masson, Mimoux, Pau, & Abitbol, 1989; Chae, Choi, Kang, Choi, & Jin, 2001). Physiological changes associated with the premenstrual period include vocal fold edema, erythema, and increased presence of microvarices (Abitbol et al., 1989). Additionally, Higgins and Saxman (1989) reported an increase in the magnitude of frequency perturbation during ovulation. They suggested that fluctuations in ovarian hormone levels alter neurotransmitter levels, which subsequently affect laryngeal motor control.

More recently, Newman and colleagues (Newman, Butler, Hammond, & Gray, 2000) documented evidence of hormone receptors within human vocal fold tissue. A significant difference relative to sex was observed, with progesterone and androgen receptors more likely to be present in male vocal fold tissue. Newman et al. proposed that "differences in male and female vocal function may be explained by a hormone receptor discrepancy" (p. 80). Although preliminary, such findings may be useful in determining why F_0 SD/STSD values would be greater for women than men. Further investigation of the role of hormones upon vocal function is warranted.

Alternatively, the use of an oral contraceptive may have contributed to increased F_0 SD/STSD. Eighteen of the 28 young women in the current study used some form of oral contraceptive. While not conclusive, there is some evidence to support the concept that use of synthetic hormones can affect vocal quality, and possibly vocal fold function. Boulet and Oddens (1996) surveyed 48 professional female singers regarding vocal

changes near or during menopause. Thirty-seven percent of the respondents associated use of oral contraceptives with voice changes, and 11% of these women reported that they had actually experienced changes in their voices while taking oral contraceptives. Using videostroboscopy, Wendler and colleagues (Wendler, Sieger, Schelhorn, Klinger, Gurr, Kaufmann, Aydinlik, & Braunschweig, 1995) found a "slight tendency" (but not statistically significant) for incomplete vocal fold closure and increased vibratory irregularity among women taking Microgyn (an oral contraceptive containing 0.03 mcg ethinyl estradiol and 0.15 mcg levonorgestrel). Such changes in vocal fold function, although slight, may have further contributed to increased F_0 SD/STSD for the young women.

For the elderly speakers, there was no significant difference in F_0 SD/STSD between men and women. One possible explanation for these findings may be due to absence of hormonal influences upon vocal fold vibration in the elderly women. While young women may exhibit increased F_0 SD/STSD compared to men of similar age due to hormonal factors and/or oral contraceptive use, such factors would not be present in this population. Indeed, Newman et al. (2000) noted a decline in progesterone receptors in the vocal fold tissue of elderly subjects (with no differentiation according to sex). Hence, a significant difference between elderly men and women would not be found. Rather, any factors which may contribute to increased phonatory instability (i.e., drying of the laryngeal mucosa) appear to affect men and women similarly as they age.

There was a trend for F_0 SD to decrease with age for women and increase with age for men. These age-related shifts, however, were not significant for either group of speakers. Previous investigators have reported increased F_0 SD for elderly women

(Decoster & Debruyne, 1997; Linville & Fisher, 1985a, b; Stoicheff, 1981), indicating reduced phonatory stability.

One possible reason for the conflicting results may be due to differences in procedure. The participants in Stoicheff's (1981) study were asked to read the Rainbow Passage, rather than sustain an isolated vowel for a specified period of time. Considering the complex requirements of speech production and the documented indices of declining coordination of the laryngeal, articulatory, and respiratory systems with advancing age (i.e., reduced rate of speaking, imprecise articulation, shorter voice onset time) [Amerman & Parnell, 1982; Hartman, 1979; Morris & Brown, 1987; Ryan & Burk, 1974; Shuey, 1989], it is possible that increased phonatory instability in Stoicheff's study was related to the task as well as to the age of the participants.

Additional procedural differences exist even when the task of sustained vowel phonation is maintained. In the present study, subjects were asked to produce the vowel / / at a comfortable pitch and loudness level. In contrast, participants in Linville and Fisher's (1985a, b) investigations were instructed to phonate the vowel /ae/ at a specified frequency and loudness level (200-220 Hz., 68-72 dB SPL). Note that the range of 200-220 Hz. is comparable to data frequently reported for young female speakers, while elderly women frequently exhibit a lower F_0. Although habitual F_0 data was not reported in Linville's studies, it is conceivable that the elderly speakers were phonating at an unnatural level. The attempt to maintain phonation at this specified level may have resulted in increased instability of the vocal mechanism. Elderly speakers must deal with loss of coordination in all systems involved in speech production; the requirement that voice be produced and maintained at a predetermined level may have further

compromised the system and result in increased instability. Indeed, prior investigations have reported no effect of age upon F_0 variability measures when F_0 was not controlled (i.e, Morris, Brown, & Michel, 1989).

The Effect of Age and Sex Upon the Aerodynamic Measures

It was hypothesized that the amplitude-based glottal airflow measures would differentiate between young and elderly speakers and that these age-related differences would be greater for men than for women. It was also hypothesized that the male speakers, regardless of age, would demonstrate greater values for the amplitude-based glottal airflow measurements than the female speakers.

Peak flow and AC flow. Two of the measures, peak glottal airflow and AC flow, demonstrated a significant main effect for age. The observation of increased AC flow in conjunction with peak flow is expected, considering AC flow is a derivative of peak flow (AC flow = peak flow minus minimum flow [Hertegard & Gauffin, 1991; Higgins & Saxman, 1991]). It is difficult to determine the functional significance of an age-related effect for these measures, as no significant effect of age was observed for either measure when sex was included as a factor (see Table 3-3). This finding was true for both women and men. Prior investigations have demonstrated no significant age-related effect for either peak flow or AC flow for women (Higgins & Saxman, 1991; Sapienza & Dutka, 1996), which agree with earlier reports of no significant age-related effect upon average airflow rates for women (Biever & Bless, 1989; Hoit & Hixon, 1992; Morris & Brown, 1987).

The lack of significant differences in airflow rates between young and elderly women indicates that the laryngeal valving economy is not significantly affected by age,

at least for women (Higgins & Saxman, 1991). One possible explanation for these results may be related to the persistent maintenance of a glottal gap during phonation. Biever and Bless (1989) demonstrated that while a posterior glottal gap predominates the glottal configuration of young women, elderly women may exhibit a posterior, mid-membranous, or anterior glottal gap. In addition, they noted that the elderly women in their study who exhibited mid-membranous gaps did not have concomitant higher airflow rates during sustained vowel production. According to Isshiki and von Leden (1964, cf. Biever & Bless), these results indicate that a "mild degree of incomplete approximation may not affect the flow rate" (p. 127). In the present study, it is difficult to determine if the elderly women presented with mid-membranous gaps, as videostroboscopy was not utilized. Further investigation of this relationship should be completed, perhaps through comparisons of types of glottal gap configurations with phonatory airflow rates.

As previously stated, post hoc analysis revealed no significant age-related differences for men concerning the measures of peak flow and AC flow. These results differ from previous studies that have reported significant differences between young and elderly men in terms of airflow measures. Melcon et al. (1989) reported significantly greater average airflow rates for elderly men compared to young men while Higgins and Saxman (1991) reported a significant increase in flow amplitude rates with age. The finding of greater airflow rates among elderly men would support anatomical evidence of degeneration and atrophy of the vocal folds (Honjo & Isshiki, 1980; Kahane, 1987), leading to reduced vocal fold closure.

It is difficult to explain the lack of significant differences for peak flow and AC flow between the young and elderly men in the present study. One may speculate that the

elderly men who participated in the current study were in very good physical condition, thus potentially negating to some extent the degenerative effects of aging (Ramig & Ringel, 1983). However, subject selection in previous studies was also based on a number of health-related criteria, so it is unlikely that participant health played a significant factor.

Alternatively, one may conclude that conflicting results of this study and previous research may be due to procedural differences. For example, Melcon et al. (1989) reported decreased laryngeal control of airflow in elderly men were based on data obtained from average airflow measures. Measures involving average airflow rates, however, may be influenced by the supraglottal articulators and resonating structures (Rothenberg, 1973). In contrast, the measures of peak flow and alternating flow are obtained through inverse-filtering of the airflow waveform. Inverse-filtering, as discussed earlier, is a process by which the effects of the supraglottic articulators and resonators are mathematically cancelled in order to obtain a more valid estimate of airflow through the glottis. Cancellation of the effects of the supraglottic structures may be critical when considering the effects of the aging process upon vocal fold function, given the documented reductions in the rate and extent of articulatory movements with age (Benjamin, 1982; Liss, Weismer, & Rosenbek, 1990; Sonies, Baum, & Shawker, 1984; Weismer & Liss, 1991) which have resulted in subtle acoustic effects (i.e., slower vowel formant transition rates, increased stop closure intervals, increased spirantization). In addition, a number of age-related alterations of the vocal tract may occur, including growth of the craniofacial skeleton throughout adulthood, atrophy of the pharyngeal musculature, and lengthening of the vocal tract due to lowering of the larynx in the neck

(Kahane, 1980; Linville, 2001). The combined effect of these changes may be sufficient to demonstrate an age-related increase in average airflow rates.

Another possible explanation for the differing results may be due to the age of the subjects involved. In the present study, the elderly men ranged from 65 to 75 years of age, with a mean age of 69 years. In the Higgins and Saxman's (1991) study, the elderly men ranged in age from 70 to 80 years of age, with a mean age of 75 years. These subjects were slightly older than those included in the current study. Perhaps the effects of aging upon the laryngeal mechanism do not significantly alter laryngeal function until advanced old age, within the range of 75 to 80 years of age.

Minimum glottal airflow: Although the results of the analysis revealed a significant sex x age interaction for minimum glottal airflow, subsequent comparisons demonstrated no significant differences in minimum flow rates between men and women or between young and elderly speakers of either sex. The lack of significant differences in minimum flow rates between men and women corresponds with prior reports. Holmberg et al. (1988; 1989) reported no significant difference in minimum flow rates for young men and women during sustained vowel production, while Higgins and Saxman (1991) reported no significant differences in minimum flow rates between young or elderly men and women during both sustained vowel production and syllable repetition. There was a nonsignificant trend, however, for the young women to demonstrate the highest minimum flow rates among all groups of participants. High minimum flow values in young women are assumed to be related to the presence of a posterior glottal chink during the closed phase of the vibratory cycle (Biever & Bless, 1989; Hertegard & Gauffin, 1995; Holmberg et al., 1988; Sodersten et al., 1995).

Minimum flow rates also did not differ significantly between young and elderly women, or between young and elderly men. Lack of a significant effect of age upon minimum flow rates provides additional support for the notion that the observed anatomical changes (i.e., Kahane, 1987) do not affect vocal fold closure to an appreciable extent, at least for this age range of elderly subjects. In women, this may be attributed to the persistent maintenance of a glottal gap during phonation, as previously discussed. The continued presence of a glottal gap in both young and elderly women, whether it is located posteriorly, mid-membranously, or anteriorly, may not allow for significant changes in minimum flow rates with age.

For the male speakers, the lack of a significant age difference again indicates that chronological aging plays a minor role in physiological function. While there may be evidence of vocal fold atrophy in elderly individuals (Honjo & Isshiki, 1980), it does not appear to be extensive enough to warrant changes in glottal airflow rates. Additionally, it may be that the overall physical health of these speakers negated the effects of aging upon the laryngeal system, as healthy speakers appear to be able to adequately compensate for degeneration of the laryngeal structures (Ramig & Ringel, 1983).

Maximum flow declination rate: Maximum flow declination rate has been defined as the "maximum rate of decrease in airflow" and corresponds to the negative peak of the differentiated airflow waveform (Gauffin & Sundberg, 1989). In general, higher MFDR values have been reported for men compared to women (Holmberg et al., 1988; 1994). The present study is in agreement with previous findings. Both young and elderly men exhibited significantly higher MFDR values compared to the young and elderly women, respectively. Holmberg et al. (1988) suggested that higher MFDR

values indicate an increased closing velocity and more abrupt closure of the vocal folds during phonation in men, which contributes to greater energy in the higher frequencies of the source spectrum. This higher amplitude harmonic spectrum is sufficient to override any turbulent noise created from the flow of air through the posterior glottis during the closed phase of the vibratory cycle (i.e., minimum flow). In women, however, this turbulence is more apparent due to the less abrupt closure of the vocal folds, which contributes to a rapid decline in the harmonic spectrum. Hence, women's voices are perceived as slightly breathy due to the combined effect of increased minimum flow and reduced MFDR.

Data concerning the effect of age upon MFDR has not been previously reported. In the present study, no significant age-related difference in MFDR was found for either men or women. Given that no significant age-related differences in any of the aerodynamic measures was observed for either the men nor the women in the present study, perhaps this result should be expected. The only significant effect of age upon vocal function for the variables included in this study was a decline in F_0 for elderly women. Hence, while certain perceptual characteristics are associated with the aging voice, these characteristics do not appear to be associated with significant alterations in laryngeal control of airflow. Given that voice is inherently multi-dimensional, the perceptually salient features of the aging voice appear to reflect the interaction of the parts rather than a single entity that is significantly different.

The Effect of Sex and Intensity upon the Acoustic and Aerodynamic Measures

For the acoustic measures, it was hypothesized that fundamental frequency would increase with increased intensity, while fundamental frequency standard deviation would

decrease with increased intensity. For the aerodynamic measures, it was hypothesized that the measures of peak flow, AC flow, and MFDR would increase with increased intensity. Minimum flow and DC/PK were predicted to decrease with increased intensity.

Fundamental Frequency, Maximum Flow Declination Rate, and Alternating Glottal Airflow: An increase in F_0 with increased intensity is an accepted and well-documented phenomenon (Sundberg, 1987, cf. Baker et al., 2001; Titze, 1989). As discussed by Titze (1994), the increase in F_0 associated with increased vocal intensity occurs due to increased amplitude of vibration as a result of increased lung pressure (Titze, 1994). The increased lung pressure increases the depth of vibration, thus increasing the speed of vibration. The increase in F_0 may also result from increased activity of the thyroarytenoid and increased subglottal pressure (Titze, 1989; 1994). Increased vocal intensity generally requires increased airflow, which would result in increased subglottal pressure. Increased vocal fold tension may be required to control the mounting subglottal pressure. Increased vocal fold tension may be achieved by contraction of the cricothyroid and/or thyroarytenoid, which would serve to reduce the effective vibrating mass of the vocal folds. Reducing the mass of the vocal folds is a contributing factor to increasing the rate of vibration, and therefore, fundamental frequency. Hence, increased loudness is associated with increased frequency of vibration.

The associated increase in F_0 with increased intensity may also result from changes in the supraglottic vocal tract. According to the source-filter theory of vowel production, "the spectrum of a vowel is the spectrum of the glottal source filtered by the

vocal tract" (Titze, 1994). In other words, the vibration of the vocal folds provides the glottal source, which is modified by the shape of the supraglottic vocal tract and position of the articulators. In terms of increasing intensity, the position of the articulators (and thus the shape of the supraglottic vocal tract) would have an effect upon F_0 during loud phonation. Although not documented, it is possible that the speakers may have increased mandibular excursion (i.e., wider mouth opening) while phonating /ɑ/ at a higher intensity level. The increase in mouth opening would have resulted in changes in the position of the articulators, however slight, which would have led to alterations in formant frequency structure, specifically F_1 and F_2. Since changes in F_1 and F_2 can affect F_0 (Sapir, 1989), the increase in mouth opening during loud phonation may have contributed to the increase in F_0.

As would be expected, women continued to generate significantly higher F_0 values compared to men while phonating at a louder level. Additionally, higher AC flow rates and MFDR values were generated by men compared to women during both intensity conditions. These results are in agreement with previously reported data (Holmberg et al., 1988).

Consistent with previously reported data, the women in the present study demonstrated a significant increase in F_0 with increased intensity (Baker et al., 2001; Holmberg et al., 1988; Isshiki, 1964). In contrast, there was not a significant increase in F_0 with increased intensity for men. One possible reason for these differing results between men and women may be related to the mechanism employed to increase vocal intensity. The women in the present study may have relied more heavily upon internal laryngeal adjustments (i.e., increased tension of the vocal folds to increase glottal

resistance and ultimately, increased subglottal pressure) to achieve increased vocal loudness (Tanaka & Masahiro, 1986; Titze, 1994). Indeed, Sodersten et al. (1995) found that the women in their study demonstrated increased vocal fold closure during loud phonation, which may have occurred due to increased laryngeal tension.

In contrast, the men may have relied predominantly on increased expiratory airflow. Support for this possibility comes from the finding that both MFDR and AC flow increased significantly with intensity for men but not for women. Recall that MFDR refers to the rate of airflow change at the moment of closure, while AC flow serves as an index of the magnitude of vocal fold vibration. Titze and colleagues demonstrated that the intensity of the sound produced is dependent upon the velocity of vocal fold closure (Sundberg, Titze, & Scherer, 1993; Titze, 1994; Titze & Sundberg, 1992). Holmberg et al. (1988) noted that such a finding supported van den Berg's (1957) theory the vocal folds close at a higher rate of speed with increased airflow through the glottis, thus resulting in higher MFDR values. In the present study, MFDR values increased with intensity for the men but not for women. Additionally, the measure of AC flow significantly increased with increased intensity for men but not for women in the present study, indicating that the magnitude of vocal fold vibration increased from comfortable to loud phonation. Prior research has indicated similar results, with a high correlation between MFDR and AC flow (Holmberg et al., 1988). These two measures were also significantly correlated with each other in the present study (see Table 5). Hence, not only does the speed of vocal fold closure increase during loud phonation, but the magnitude of vocal fold vibration also increases. These changes would result not only from increased vocal fold tension, but also from increased respiratory drive. It is

possible that speakers may vary in the extent to which they employ these mechanisms, thus contributing to the differing results for men and women in the present study.

Peak glottal airflow and minimum glottal airflow: In agreement with earlier reports of increased peak flow rates for men compared to women as a result of the size differential of the larynx (Holmberg et al., 1988; 1989), men continued to generate significantly higher peak flow rates than women regardless of intensity condition. In addition, the lack of a significant difference in minimum flow rates between men and women during both comfortable and loud phonation supports previous findings that this measure is equivalent between sexes (Holmberg et al., 1988; 1989).

Contrary to predictions, however, there were not a significant effect of intensity upon peak or minimum glottal airflow for either men or women. Lack of a significant change in minimum flow for loud phonation agrees with previously reported data (Holmberg et al., 1988), indicating that small increases in vocal intensity (i.e., 10 dB) do not significantly alter vocal fold approximation during the closed phase of the vibratory cycle.

Peak flow was not significantly altered by increased vocal intensity for either men or women. These results differ from those previously reported by Sodersten et al. (1995) and Holmberg et al. (1988) who reported increased peak flow rates in men and women with increased intensity. In women, such a finding may be expected from concurrent data obtained in the present study. Neither alternating flow nor minimum flow rates were significantly affected by intensity level among the female speakers, both of which are components of peak flow. In contrast, the male speakers demonstrated a significant increase in AC flow with increased intensity. Peak flow would also be expected to

increase in conjunction with AC flow during loud phonation, as both may serve as indices of the vibratory magnitude. Since peak flow is comprised of both AC flow and DC flow, however, it is possible that the inclusion of DC flow resulted in nonsignificant differences for the composite measure of peak flow.

The Effect of Sex, Age, and Intensity upon the Aerodynamic Measures

Minimum flow/peak flow ratio: An interaction of sex, age, and intensity was found for the ratio of minimum flow to peak flow (DC/PK). This ratio was included as a physiological correlate of breathiness. A high ratio score has been correlated with the perception of breathiness in dysphonic speakers (Fritzell et al., 1986). It was hypothesized the DC/PK ratio would be significantly greater for young women compared to elderly women, but significantly greater for elderly men compared to the young men. It was also hypothesized that the DC/PK ratio would decrease with increased intensity. Although there was a general trend within the data to support these hypotheses (see Tables 2 and 3), these differences did not reach statistical significance.

One possible reason for the lack of significant findings may be due to the use of normal subjects. In the study by Fritzell et al. (1986), the subjects demonstrated significant breathiness due to a pathological condition (i.e., vocal fold paralysis, vocal fold bowing, sulci). The subjects in the present study, however, were normal and thus did not demonstrate significant breathiness. It is possible that this measure is not sensitive to small changes in laryngeal valving associated with normal aging.

Significant differences in DC/PK were found, however, between young men and women, and between elderly men and women. Regardless of vocal intensity, the young women exhibited higher DC/PK ratios compared to the young men. Such a finding

would be expected given the high prevalence of a posterior glottal gap in women, which is thought to contribute to a slightly more breathy quality in young women's voices (Biever & Bless, 1989; Holmberg et al., 1988).

Similarly, elderly women consistently demonstrated significantly higher DC/PK ratios compared to elderly men. These results were not expected given the noted occurrence of vocal fold bowing in elderly men and vocal fold edema in elderly women (Honjo & Isshiki, 1980), which would conceivably result in increased breathiness for elderly men. It is possible, however, that elderly women continued to exhibit higher DC/PK ratios compared to elderly men due to the persistent maintenance of a glottal gap. While the placement of the glottal gap is located more anteriorly in healthy, non-smoking, elderly women continue to exhibit incomplete closure of the vocal folds during phonation (Biever & Bless, 1989). In sum, the difference in anatomy across the sexes is distinct enough to result in higher DC/PK ratios for women compared to men of similar ages.

Perceptual Analysis

Inter-rater reliability: As previously stated, intra-rater reliability was low to high, ranging from r^2=.42 to r^2=.83 (see Table 2-3). Inter-rater reliability was low to moderate, ranging from r^2=.05 to r^2=.59 (see Tables 2-7 and 2-8). Several reasons may exist for the poor correlations between the judges. First, previous research has shown that expert listeners frequently differ in the use of strategies employed to rate both pathological and normal voices (Kreiman et al., 1990; Kreiman, Gerratt, Precoda, & Berke, 1992). These differences may be due to clinical training and experience. Additionally, Kreiman et al. (1990) noted that clinicians may have developed more than one prototype, or internal

standard, for various pathological conditions, which may further limit the ability of individual clinicians to agree on one particular rating for a voice. Such restrictions may have contributed to the low inter-rater reliability in the present study, given that limited nature of the rating scale (a rating of "0", "1", "2", or "3" only).

Another possible reason for the low reliability may be due to the nature of the task itself. The judges were asked to rate only one feature of the voice (breathiness), a strategy rarely employed in clinical settings. Hence, it may have been difficult for the listeners to focus on only one vocal attribute. A recent study by Kreiman and Gerratt (2000) demonstrated that listeners experience difficulty in rating an isolated measure of vocal quality. Indeed, the authors demonstrated that listeners were more reliable in rating synthetic stimuli compared to natural pathologic voices, indicating that it is difficult to isolate a single perceptual dimension from such a complex stimulus as voice.

Additionally, all the samples were those of normal speakers, which may have further limited the ability of the judges to reliably rate the samples (Kreiman & Gerratt, 2000). As the samples in the present study were those of *normal* speakers with only small variations in breathiness, it is likely that the judges had a difficult time in reliably rating these small changes. Indeed, it is notable that intra-rater reliability decreased from comfortable to loud intensity, indicating greater difficulty in agreeing on a rating of perceived breathiness under this condition. This is possible considering that increased intensity results in reduced breathiness due to increased vocal fold closure, which further reduces the extent to which breathiness is likely to vary. Support for this hypothesis may also be found in a previous study conducted by Rabinov, Kreiman, Gerratt, and Bielamowicz (1995). Rabinov and colleagues examined the relative reliability of

perceptual ratings of roughness and acoustic measures of jitter and found that listener agreement actually increased as dysphonic severity increased. Hence, it appears that large variations in vocal quality are more reliably distinguished than small aberrations.

Several of the judges also commented that rating breathiness (or any single vocal quality) for this population had been difficult due to the lack of extreme contrasts of no breathiness versus severe breathiness. These findings differ from those reported by Shrivastav (submitted), who suggested that instructing listeners to focus on breathiness and "avoid making judgments on pitch" may have improved the listener's ability to attend to the quality of breathiness. It should be noted, however, that the voice stimuli used in Shrivastav's study were those of individuals with disordered vocal quality, rather than those with normal voices.

Listener Perception of Breathiness: It was hypothesized that the voices of women would be perceived as significantly more breathy than the voices of men. Three of the raters did perceive women as having breathier voices than men. However, two of the raters (#2 and #4) tended to perceive increased breathiness among the men compared to the women in their respective age groups. The level of experience did not seem to be a factor in this outcome, as one of the raters had 17 years of experience and the other one had 9 years. As stated previously, one possible explanation for these conflicting findings may have been the exclusive use of normal subjects, in whom only minute differences in perceived breathiness may occur, thus making it difficult to reliably judge the degree of breathiness. Additionally, rater #4 exhibited the lowest intra-rater reliability (r^2=.42), which suggests that this rater may have not judged all samples equally. Caution should therefore be taken in interpreting these results.

With regard to age, it was hypothesized that the voices of the elderly men would be perceived as being more breathy than those of the younger men, presumably due to vocal fold atrophy and other degenerative changes within the larynx and respiratory system. As noted previously, the elderly men were generally perceived as more breathy compared to the younger speakers. These results agree with earlier reports of listeners' perceptions of elderly men (i.e., Ryan & Burk, 1980). This increased perception of breathiness is likely due to the combined effect of declining respiratory function and reduced efficiency of laryngeal valving. The data obtained for minimum flow and the DC/PK ratio in the present study provide an indication of declining laryngeal control of pulmonary airflow with age. The lack of nonsignificant findings for these measures, however, indicates that while these measures may not be sensitive enough to reflect age-related changes in the phonatory mechanism, these modifications appear to be extensive enough to affect listener perception of vocal quality, at least for elderly men.

For the elderly women, in contrast, it was proposed that the voices of elderly women would be perceived as exhibiting less breathiness compared to the young women. Slight breathiness in young women is considered normal, due to the presence of the posterior glottal gap previously mentioned (Biever and Bless, 1989). The voices of elderly women, however, have been described as rough and hoarse, due in part to increased mass of the vocal folds resulting from post-menopausal hormonal changes (Honjo & Isshiki, 1980).

The results of the present study do not support this hypothesis. Similar to the results obtained for the men, the voices of the elderly women were perceived as more breathy than the young women. These results conflict with the physiologic data obtained

in the present study. No significant differences were found between the young and elderly women on measures indicative of air loss during phonation (i.e., minimum flow and DC/PK). Interestingly, there was a trend in the data for these measures to be lower for elderly women, suggesting more complete closure of the vocal folds during phonation.

It was also hypothesized that increased vocal intensity would result in reduced perception of breathiness for both the elderly and young speakers. The results of the present study provide support for this hypothesis. All groups of speakers were perceived as less breathy when vocal intensity was increased. Given that minimum flow rates were not significantly affected by increased intensity, it is unlikely that the reduced perception of breathiness is due to greater vocal fold closure. Rather, the decrease in vocal breathiness is likely due to other factors. As discussed earlier, the male subjects appeared to increase vocal intensity through the use of increased respiratory support, as indicated by the significant increase in AC flow rates and MFDR. According to Holmberg et al. (1988) the observance of higher MFDR rates in men (compared to women) in their study suggested a higher closing velocity and more abrupt closure of the vocal folds, which should contribute to a source spectrum with greater energy in the higher frequencies for men (cf. Fant, 1979; Isshiki, 1981). Holmberg et al. suggested that the turbulent noise generated by the minimum flow component would be masked by the higher amplitude harmonic spectrum of the male voice, thus contributing to reduced breathiness in male voices. With regard to the present study, the increase in MFDR noted in men with increased intensity may have likewise contributed to perception of reduced breathiness.

For women, the reduction in perceived breathiness is associated with a slightly different mechanism. In the present study, women appeared to rely more heavily upon increased laryngeal tension to achieve increase vocal loudness, as evidenced by the significant increase in F_0 for women but not for men during loud phonation. The increase in F_0 appears to serve a similar function as that noted for increased MFDR in men. That is, increased F_0 results in greater energy associated with the harmonic spectrum, which in turn, serves to mask the turbulent airflow associated with the minimum flow component and a reduction in perceived vocal breathiness.

Correlation of perceptual ratings with airflow measures: It was initially hypothesized that the ratings of breathiness would be significantly correlated with the physiological measures of minimum flow, MFDR, and DC/PK. Across all listeners, however, the perceived breathiness of the speakers did not show high correlations with any of these measurements. Previous data have demonstrated moderate correlations of breathiness ratings with minimum flow and DC/PK among normal speakers (Sodersten et al., 1995). The conflicting results may be due to methodological differences and/or subject composition. These differences primarily involve the exclusive use of normal subjects with minimal variations in breathiness. Combined with the reported variability among aerodynamic measures (Holmberg et al., 1988), and the increased variability in speech production measures among elderly speakers (i.e., Linville, 1988; Morris & Brown, 1994), it is possible that these factors negated any significant correlations among the measures and the perception of breathiness.

Variability in the Elderly Population

Previous studies on the effects of aging upon voice production have reported significant differences between young and elderly speakers for the measures of F_0, F_0 SD and AC flow (Honjo & Isshiki, 1980; Higgins & Saxman, 1991; Linville & Fisher, 1985a, b; Mysak, 1959; Orlikoff, 1990). In the present study, the only significant finding related to age was a lower mean F_0 for the elderly women compared to the young women. No other age-related contrasts were significant.

One possible reason for the differing results between this study and that of previous studies may be due to the increased variability among elderly speakers. For example, in some studies reporting acoustic characteristics associated with voice production, a lack of significant age-related differences appears to be due to increased variability for the elderly speakers (Biever & Bless, 1989; McGlone & Hollien, 1969; Wilcox & Horii, 1980). This increased variability in several acoustic measures has been well documented for elderly women (Benjamin, 1981; Biever & Bless, 1989; Brown et al., 1989; 1990; Linville & Fisher, 1985b; Linville et al., 1990; Mysak, 1959; Scukanec, Petrosino, & Ratstatter, 1992; Wilcox & Horii, 1980) and has also been observed in elderly males (Liss, Weismer, & Rosenbek, 1990).

For the aerodynamic measures, intra-subject variability may be related to variations in SPL. Holmberg et al. (1994) demonstrated that greater than 50% of the variability associated with MFDR and AC flow was accounted for by variation in SPL. Only a small portion of the variability in the amplitude-based measures (i.e., peak flow, minimum flow), however, was related to variations in SPL, indicating that other factors may be responsible for the variation.

To account for intra- and inter-speaker variation in the present study, SPL was included as a covariate in the statistical analysis as several of the measures were significantly correlated. Additionally, the sample size for each participant group was determined based on a power analysis of variability in peak glottal airflow rates among elderly women. Sapienza and Dutka (1996) reported that this measure exhibited the largest range of variation among the elderly women in their study. It was hoped that the combination of an adequate sample size and the inclusion of SPL as a covariate would be effective in reducing both intra- and inter-subject variability associated with the measures of vocal fold function. However, it is possible that even these measures were not sufficient to account for speaker variability, particularly among the elderly speakers. The process of aging differs between individuals according to sex, race, overall health, and even within the same individual according to specific physiological systems (Ramig et al., 2001). Linville (2001, personal communication) suggested that individual differences in aging may be too great to be accounted for by measures such as controlling sample size. In other words, the number of subjects required to overcome variability in the aged population may be too large to be feasible. It is worth noting that, in the present study, despite an apparently adequate sample size and accounting for SPL level differences, inter-speaker variability as computed by the coefficient of variation (COV) was generally greater for the elderly subjects compared to their younger counterparts across both intensity conditions (see Appendix I). This relatively high inter-speaker variability among the elderly speakers may have contributed to the lack of significant age-related differences.

Procedural Differences

Another possibility that may explain the lack of significant age-related differences among the amplitude-based glottal airflow measurements may be due to the nature of the task itself. Much of the previous work conducted on the effects of aging and airflow parameters associated with phonation has been completed using a sustained phonation task. Few studies have included a connected speech task to examine differences among young and elderly speakers (Higgins and Saxman, 1991; 1993). Although few differences were found among the airflow measures between young and elderly women, the elderly men exhibited several significant differences compared to the young men, particularly during the syllable repetition task. As syllable repetition more closely approximates the natural speech pattern, it is possible that this type of task was more sensitive to age-related changes in vocal fold function. Indeed, Higgins and Saxman (1993) noted that individuals with compromised vocal mechanisms, either as a result of aging or damage, significantly increase vocal fold tension and length when required to maintain glottal closure for a period of time, such as during a sustained phonation task. This type of adjustment may negate any effects that laryngeal muscular atrophy and/or reduced laryngeal control would have on manipulation of airflow.

Since sustained phonation does not involve movement and complex, fine adjustments of the articulatory, laryngeal and/or respiratory systems, as would be expected during a connected speech, this type of task may not sufficiently tax the phonatory system to reflect a breakdown in the laryngeal control of airflow. Additionally, it should be noted that many of the perceptual characteristics associated with the elderly voice involves those apparent during connected speech (i.e., phrasing

changes, hesitancy, reduced rate of articulation, imprecise consonantal production, etc. [Ptacek & Sander, 1966a; Ptacek et al., 1966; Ryan & Burk, 1974]). Hoit and Hixon (1992) proposed that the conflicting results of larger air volume expenditure during speech for women (Hoit et al., 1989) but no significant decline in laryngeal airway resistance was due to the different demands of sustained phonation vs. connected speech. During connected speech, they suggested that the air "wastage" that occurs among elderly speakers may be due to reduced agility of the aged larynx to move "…in and out of the airway, a potential consequence of age-related reduction in the number of motor units and a larger motor unit size (Cooper, 1990)" [p. 311]. In contrast, once the desired position of the larynx has been achieved for the purpose of phonating for an extended period of time, laryngeal valving efficiency is similar for both young and elderly adults.

Limitations of Study

It is important to note the methodological limitations of this study that may affect the generalizability of the results. The purpose of this study was to examine the effects of biological aging and sex upon vocal function. To accomplish this goal, healthy young and elderly adults with normal vocal quality were recruited as participants. The decision to include an individual in the study was based, in part, upon subjective and objective assessment of vocal quality. This assessment, however, did not include visual inspection of the larynx. Hence, lack of vocal pathology in all subjects cannot be fully assured, even though all subjects met the screening criteria (see pages 33-34).

The decision not to include visual inspection of the larynx (i.e., video-laryngoscopy) was based on a number of factors. First, inclusion of videolaryngoscopy would have reduced the number of subjects willing to participate in the study. Many of

the subjects were willing to have their voice recorded but were very opposed to the idea of undergoing a laryngoscopic examination. Secondly, some individuals may not have been able to tolerate laryngeal examination through the use of a rigid endoscope, which would have resulted in loss of data and/or exclusion from the study, thereby further limiting the number of potential subjects. Thirdly, the screening criteria used in the present study has been well documented in the literature (i.e., Boucher & Lamontagne, 2001; Koenig, 2001; Linville et al., 1990; Liss et al., 1990; Morris & Brown, 1994; Orlikoff, 1990; Sapienza & Stathopoulos, 1995). Ninety-five percent of studies reviewed from 1995-2001 that involved the use of "normal controls" did not include endoscopy, or at least did not specify its use. Finally, as previously stated, *MDVP* has been shown to be both reliable and valid in distinguishing normal from disordered voice (Cimino & Sapienza, 1999; Kent et al., 1999; Natour et al., in press).

Another limitation to this study is that the elderly subjects ranged in age from 65 to 75 years. It is possible that the lower age limit of 65 years was too low to allow for observance of significant aging effects. As previously stated, the lower age limit of 65 years was established in order to insure that all participants were healthy and able to meet the inclusionary critieria. Raising the lower age limit to 70 or 75 years would have limited the number of available participants who met the screening criteria. However, as indicated by the results of previous studies (i.e., Higgins & Saxman, 1991), the inclusion of individuals over the age of 75 years may be necessary to demonstrate significant age-related changes in vocal function.

Another limitation to this study is that only healthy Caucasian men and women were recruited as participants. The effect of aging upon voice production in other races

and ethnic groups has not been studied, and there is some evidence to suggest that aging differs according to race (Ramig et al., 2000). Further exploration of this possibility is warranted.

CHAPTER 5
SUMMARY AND CONCLUSIONS

Summary

The results of the present study are summarized in conjunction with the hypotheses set forth in Chapter 2. These findings are as follows:

The Effect of Sex upon the Acoustic, Aerodynamic, and Perceptual Measures

The results of the present study demonstrated significantly lower F_0 values for men compared to women, in agreement with previous research. The results of the present study also demonstrated significantly higher F_0 SD/STSD values for young women in comparison to young men. Although it was conjectured that this difference was due to fluctuations in hormonal levels, as suggested by Higgins and Saxman (1993), this hypothesis cannot be proven based on the results of this study. Further investigation of the mechanisms responsible for increased frequency perturbation in the female voice is needed.

The results of the present study also revealed significantly greater peak flow, AC flow, and MFDR rates for the men compared to the women. These results are in agreement with previous research, which suggests that the greater flow rates in men are due to the overall larger size of the male larynx. No significant difference was observed

in minimum flow rates between men and women, which is also concordant with previous data. Finally, the results of the study revealed significantly higher DC/PK ratios for women compared to men, which would be expected based on the persistent presence of a glottal gap during phonation in the majority of women.

The results of the perceptual task were conflicting. Although a number of the raters judged the women to be more breathy compared to the men, two of the raters perceived the voices of men to be more breathy. While these results appear to contradict conventional thinking regarding auditory perception of male and female voices, it is likely that the sole use of normal voices, with minimal contrasts, contributed to these different patterns. In addition, internal biases of the individual raters may have contributed to these results.

The Effect of Age upon the Acoustic, Aerodynamic, and Perceptual Measures

For the acoustic measure of F_0, there was a significant decrease in F_0 with age for women and a nonsignificant trend for F_0 to increase with age for men. These findings are in agreement with previous research, suggesting a coalescence of F_0 in elderly men and women. The measure of F_0 SD was included as an indicator of phonatory stability. Prior investigations have demonstrated a significant increase in F_0 SD with age (and thus increased phonatory instability). However, no significant differences between young and elderly speakers were found in the present study for this measure. As procedural and task differences between the present study and prior investigations may have contributed to the conflicting results, continued research concerning this measure as a distinguishing characteristic between healthy young and elderly speakers is suggested.

For the amplitude-based glottal airflow measures, the results of the present study revealed no significant age-related effect upon these parameters. These findings suggest that although there is anatomical evidence of age-related laryngeal degeneration, these changes may not be sufficient to produce significant changes in isolated measures of vocal fold function, at least during a sustained phonation task. The use of a connected speech task, which requires more complex movements and adjustments, as well as synchronicity between the phonatory and respiratory systems, may be necessary to draw out differences between young and elderly speakers. Alternatively, it may be that such changes may not be great enough to affect phonatory function in speakers younger than 75 years of age. Individuals over the age of 75 years should be included in future studies to determine if the relative stability of vocal fold function is maintained later in life.

With regard to the perceptual results, the voices of elderly men and women were perceived as more breathy in comparison to the voices of young men and women, respectively. The increased breathiness in elderly speakers may be attributed to degeneration and atrophy of vocal fold tissue, leading to incomplete closure of the vocal folds. Caution should be taken in interpreting these results, however, given the poor intra- and inter-reliability associated with the judgments.

The Effect of Intensity upon the Acoustic, Aerodynamic, and Perceptual Measures

The results of the present study revealed significant differences in both the acoustic and aerodynamic measures with increased intensity. These results also suggested possible differences between men and women in the mechanisms used to increase vocal loudness. An increase in F_0 was observed for women without concomitant increases in airflow measurements, suggesting that women relied more heavily upon

internal laryngeal adjustments to increase vocal loudness. In contrast, AC airflow and MFDR increased significantly for men with increased intensity but there was no similar increase in F_0. These findings indicate that the men may have relied predominantly upon increased respiratory drive to increase vocal loudness. As respiratory kinematic data was not obtained during this study, it is difficult to confirm this hypothesis. Future studies should incorporate both respiratory and aerodynamic assessment in the protocol to determine if actual sex-related differences exist in the control of vocal loudness.

The results of the perceptual analysis demonstrated a decrease in the perception of breathiness for all speakers. Based on the results for the acoustic and aerodynamic data, such a finding would be expected. The increase in F_0 observed for the women with increased intensity results in greater energy associated with the harmonic spectrum, thus reducing the noise associated with minimum flow during phonation. For the men, the increased amplitude of vibration and increase speed of vocal fold closure (as indicated by greater AC flow and MFDR) also serves to increase energy within the harmonic spectrum, thus also reducing the noise associated with the minimum flow component of phonation.

Conclusions

The present study was conducted to examine the effects of age, sex, and intensity upon acoustic, aerodynamic, and perceptual measures of vocal fold function. This study encompassed several acoustic and aerodynamic measures within a single design, and included the largest sample size to date. The results of this study support the coalescence model of fundamental frequency, in that F_0 significantly decreased for elderly women and demonstrated a trend to increase for elderly men. The results of this

study also demonstrated significant differences between young men and women relative to fundamental frequency stability. Possible explanations for this finding are not clear; future research should be conducted to examine whether this difference is due to hormonal influences or some other factor.

The lack of significant age-related differences among the glottal airflow measurements suggest that the effects of aging may not be great enough to produce measurable changes in vocal fold function for individuals up to 75 years of age. In other words, vocal fold function appears to remain relatively stable up to 75 years of age. These findings provide further evidence that healthy individuals exhibit minimal effects of aging upon vocal fold function. Clinically, such information may be useful in that normative data currently available may be applied to the assessment and treatment of elderly individuals with voice disorders. It is important to note, however, that the effect of aging upon vocal function in healthy individuals over the age of 75 years remains to be determined.

The results of the present study also provided evidence to support differences in vocal intensity regulation between men and women. Increased vocal intensity resulted in significant increases in distinct measures for men and women. While further research is necessary in order to better elucidate these mechanisms, the current study provides a foundation upon which future studies may be built.

Finally, the results of the present study demonstrated that expert listeners tend to identify increased breathiness in the voices of elderly speakers, regardless of sex. These findings suggest that breathiness may be a prominent component of both the elderly male *and* female voice, rather than simply being associated with the elderly male voice as is

generally considered. It may be necessary to revisit those salient features that are associated with the voices of elderly men and women, as they may not be as distinct as previously thought.

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APPENDIX A. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR YOUNG WOMEN AT A COMFORTABLE INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	257.36	5.39	60.57	0.12	0.07	0.06	-103.37	58.3
2	177.99	2.81	50.18	0.09	0.04	0.05	-72.96	44.4
3	233.12	2.28	59.60	0.09	0.03	0.06	-90.07	33.3
4	208.21	2.57	59.14	0.08	0.02	0.06	-132.47	25.0
5	262.05	3.81	60.29	0.08	0.03	0.05	-104.66	37.5
6	214.65	3.96	49.57	0.06	0.03	0.03	-53.40	50.0
7	234.90	3.26	53.64	0.04	0.01	0.03	-33.71	25.0
8	229.42	3.01	56.04	0.06	0.02	0.04	-76.59	33.3
9	216.58	2.83	60.40	0.11	0.02	0.09	-127.07	18.1
10	256.93	3.48	62.62	0.12	0.04	0.08	-183.25	33.3
11	218.21	3.03	50.18	0.07	0.04	0.03	-33.77	57.1
12	244.91	3.55	55.14	0.06	0.03	0.04	-61.21	50.0
13	232.17	4.36	53.82	0.10	0.05	0.05	-60.89	50.0
14	211.48	2.86	53.17	0.10	0.04	0.06	-95.04	40.0
15	246.74	4.00	53.77	0.07	0.03	0.04	-60.17	42.9
16	215.85	2.21	58.30	0.08	0.03	0.05	-98.29	37.5
17	230.31	2.96	53.89	0.06	0.02	0.04	-53.53	33.3
18	216.57	2.75	53.71	0.05	0.02	0.03	-59.16	40.0
19	217.96	2.78	61.01	0.10	0.04	0.06	-116.58	40.0
20	237.86	3.60	57.97	0.09	0.03	0.06	-140.35	33.3
21	195.20	2.87	55.57	0.08	0.02	0.06	-107.41	25.0
22	199.40	3.05	53.44	0.05	0.01	0.03	-65.92	20.0
23	210.28	2.73	55.01	0.08	0.04	0.04	-85.65	50.0
24	259.59	6.23	56.46	0.10	0.04	0.06	-107.22	40.0
25	225.15	3.25	58.58	0.08	0.03	0.05	-93.54	37.5
26	240.43	4.72	58.53	0.11	0.04	0.06	-101.85	36.4
27	197.88	3.24	54.72	0.14	0.07	0.07	-88.18	50.0
28	198.57	3.07	56.16	0.07	0.01	0.06	-81.05	14.3

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX B. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR YOUNG MEN AT A COMFORTABLE INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	121.50	1.16	56.67	0.10	0.02	0.09	-78.76	20.0
2	136.11	1.34	65.18	0.16	0.02	0.14	-241.87	12.5
3	114.67	1.08	56.35	0.11	0.02	0.09	-99.15	18.1
4	100.25	0.76	58.51	0.15	0.04	0.11	-170.37	26.7
5	108.80	1.05	53.51	0.09	0.03	0.06	-77.72	33.3
6	93.54	0.92	51.47	0.16	0.03	0.13	-114.39	18.5
7	113.66	1.23	52.15	0.20	0.03	0.17	-138.44	15.0
8	89.17	0.84	56.44	0.14	0.01	0.13	-107.44	7.1
9	94.73	1.00	56.05	0.11	0.02	0.09	-124.73	18.1
10	78.83	0.59	53.55	0.17	0.02	0.15	-86.36	11.8
11	104.34	1.20	52.10	0.11	0.01	0.10	-74.31	9.1
12	116.75	1.08	58.00	0.13	0.03	0.10	-118.17	23.1
13	108.06	0.96	56.38	0.14	0.03	0.11	-126.81	21.4
14	131.04	1.19	66.98	0.25	0.01	0.24	-314.50	4.0
15	120.36	1.48	59.83	0.14	0.02	0.12	-147.15	14.3
16	106.84	0.89	59.39	0.19	0.02	0.16	-228.00	10.5
17	121.03	1.61	54.06	0.18	0.03	0.15	-122.27	16.7
18	100.60	0.98	57.19	0.13	0.01	0.11	-210.84	7.7
19	122.90	1.19	64.03	0.22	0.01	0.21	-331.28	5.6
20	104.38	1.00	57.48	0.11	0.01	0.10	-119.28	9.1
21	100.98	1.13	58.05	0.13	0.01	0.10	-100.97	7.7
22	109.23	1.29	57.52	0.14	0.03	0.11	-133.87	21.4
23	98.32	1.03	52.34	0.08	0.02	0.06	-46.08	25.0
24	116.45	1.00	58.46	0.13	0.01	0.12	-110.16	7.7
25	82.91	2.47	51.19	0.16	0.06	0.10	-55.13	37.5
26	111.89	1.70	58.05	0.17	0.03	0.14	-139.30	17.7
27	98.54	0.92	53.69	0.13	0.04	0.10	-102.61	30.8
28	95.29	0.92	56.12	0.09	0.00	0.09	-93.97	0.0

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX C. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR ELDERLY WOMEN AT A COMFORTABLE INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	222.75	3.05	69.09	0.10	0.01	0.09	-197.69	10.0
2	235.97	4.20	62.48	0.14	0.05	0.10	-167.90	35.7
3	192.28	2.26	63.68	0.09	0.01	0.08	-177.59	11.1
4	201.21	3.69	53.51	0.06	0.01	0.05	-51.69	16.7
5	183.30	2.38	59.16	0.06	0.01	0.05	-76.99	16.7
6	180.16	1.88	49.73	0.13	0.06	0.08	-64.98	46.2
7	141.62	1.16	65.05	0.14	0.01	0.13	-229.72	7.1
8	157.75	1.94	55.07	0.06	0.01	0.05	-58.74	16.7
9	187.61	3.02	50.61	0.06	0.02	0.05	-40.76	33.3
10	203.68	2.32	62.47	0.08	0.01	0.08	-123.60	12.5
11	213.01	3.90	57.58	0.15	0.08	0.07	-77.17	53.3
12	189.07	2.90	56.68	0.10	0.02	0.08	-81.61	20.0
13	191.01	3.01	52.17	0.09	0.03	0.06	-70.36	33.3
14	167.18	3.32	50.99	0.06	0.03	0.03	-41.23	50.0
15	147.64	1.76	53.22	0.06	0.01	0.05	-64.13	16.7
16	160.29	2.26	54.73	0.06	0.01	0.05	-67.82	16.7
17	179.46	3.67	53.84	0.11	0.04	0.07	-97.50	36.4
18	128.32	2.32	53.20	0.08	0.03	0.05	-72.82	37.5
19	160.09	2.37	56.15	0.11	0.02	0.09	-96.84	18.2
20	177.90	2.14	57.09	0.11	0.01	0.09	-91.34	9.1
21	217.96	3.64	60.92	0.14	0.04	0.10	-146.57	28.6
22	173.81	1.97	55.43	0.09	0.02	0.07	-93.76	22.2
23	199.64	3.02	55.01	0.09	0.01	0.07	-67.35	11.1
24	291.90	5.72	60.94	0.10	0.04	0.06	-109.67	40.0
25	242.77	4.78	62.04	0.16	0.01	0.15	-157.39	6.3
26	208.30	3.23	56.33	0.12	0.04	0.08	-113.16	33.3
27	161.32	2.91	52.73	0.09	0.04	0.05	-64.52	44.4
28	191.84	2.42	64.81	0.08	0.01	0.07	-140.12	12.5

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX D. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR ELDERLY MEN AT A COMFORTABLE INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	110.49	1.54	59.26	0.26	0.04	0.22	-186.25	15.4
2	103.65	1.83	54.98	0.34	0.07	0.27	-229.68	20.0
3	172.60	2.86	63.53	0.17	0.04	0.13	-196.06	23.5
4	112.24	1.24	58.76	0.13	0.01	0.12	-148.05	7.7
5	121.69	1.15	59.84	0.21	0.03	0.17	-138.81	14.3
6	107.90	1.71	46.70	0.05	0.02	0.03	-6.42	40.0
7	114.32	1.77	52.40	0.14	0.02	0.11	-87.50	14.3
8	73.37	1.08	55.22	0.15	0.02	0.13	-132.89	13.3
9	86.90	1.17	54.94	0.19	0.04	0.15	-160.98	21.1
10	115.37	1.69	52.08	0.13	0.03	0.10	-69.51	23.1
11	102.50	2.14	58.38	0.15	0.03	0.13	-116.77	20.0
12	91.12	0.92	55.14	0.22	0.05	0.17	-126.62	22.7
13	122.43	1.90	59.30	0.11	0.01	0.11	-99.63	9.1
14	118.69	1.48	56.47	0.17	0.03	0.14	-107.26	17.7
15	125.21	1.48	64.65	0.11	0.01	0.11	-164.45	9.1
16	168.05	3.20	60.28	0.14	0.04	0.10	-122.33	28.6
17	104.87	1.50	53.19	0.10	0.02	0.08	-54.61	20.0
18	116.65	1.89	61.73	0.16	0.02	0.14	-148.96	12.5
19	73.42	1.26	46.43	0.11	0.05	0.07	-20.97	45.5
20	134.04	1.62	62.77	0.15	0.02	0.13	-175.36	13.3
21	114.42	1.25	58.92	0.17	0.02	0.15	-64.01	11.8
22	117.89	1.25	58.38	0.11	0.02	0.09	-87.39	18.1
23	99.61	1.03	58.24	0.13	0.02	0.12	-106.68	15.4
24	99.14	1.69	52.95	0.18	0.03	0.14	-78.85	16.7
25	119.02	1.55	56.81	0.22	0.07	0.15	-130.21	31.2
26	132.02	1.50	63.78	0.19	0.02	0.17	-254.49	10.5
27	118.05	1.36	53.16	0.17	0.04	0.14	-137.85	23.5
28	158.39	1.97	57.87	0.20	0.08	0.12	-175.17	40.0

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound .pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX E. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR YOUNG WOMEN AT A LOUD INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	285.00	5.55	67.41	0.12	0.06	0.07	-155.31	50.0
2	219.20	3.07	64.20	0.12	0.03	0.09	-190.61	25.0
3	261.84	2.45	67.01	0.10	0.02	0.07	-147.23	20.0
4	236.34	2.74	66.24	0.08	0.01	0.07	-186.77	12.5
5	291.42	3.99	68.04	0.09	0.02	0.06	-164.97	22.2
6	258.43	4.23	64.95	0.09	0.02	0.08	-183.55	22.2
7	272.20	3.49	63.70	0.06	0.00	0.06	-132.40	0.0
8	261.54	3.20	65.25	0.07	0.01	0.06	-150.18	14.3
9	245.21	3.00	67.77	0.11	0.01	0.10	-183.81	9.1
10	282.21	3.63	68.21	0.12	0.03	0.09	-223.71	25.0
11	260.07	3.28	64.54	0.10	0.03	0.07	-154.61	30.0
12	280.72	3.76	66.30	0.08	0.02	0.06	-152.70	25.0
13	270.00	4.59	66.06	0.12	0.03	0.08	-162.21	25.0
14	248.76	3.08	65.10	0.12	0.03	0.10	-193.64	25.0
15	283.94	4.23	65.67	0.09	0.02	0.07	-157.40	22.2
16	244.70	2.38	65.78	0.09	0.02	0.07	-156.06	22.2
17	266.71	3.18	65.37	0.08	0.01	0.07	-147.89	12.5
18	252.23	2.97	64.79	0.07	0.00	0.06	-149.92	0.0
19	245.29	2.94	67.68	0.10	0.03	0.07	-166.97	30.0
20	269.54	3.79	66.94	0.10	0.02	0.08	-211.81	20.0
21	228.65	3.07	65.48	0.09	0.01	0.08	-187.48	11.1
22	236.70	3.28	65.39	0.06	0.00	0.06	-164.64	0.0
23	245.71	2.94	65.97	0.10	0.03	0.07	-175.30	30.0
24	291.97	6.43	65.81	0.11	0.03	0.08	-182.13	27.3
25	256.85	3.44	67.57	0.08	0.02	0.07	-165.15	25.0
26	263.13	4.85	62.76	0.10	0.03	0.07	-129.86	30.0
27	223.38	3.38	60.43	0.13	0.06	0.08	-129.75	46.2
28	223.17	3.21	61.39	0.07	0.00	0.06	-118.25	0.0

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX F. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR YOUNG MEN AT A LOUD INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	138.21	1.21	64.42	0.15	0.01	0.14	-198.32	6.7
2	147.96	1.36	70.36	0.20	0.02	0.19	-337.88	10.0
3	134.76	1.15	65.89	0.16	0.01	0.15	-234.15	6.3
4	117.40	0.82	66.50	0.20	0.04	0.16	-292.07	20.0
5	131.06	1.13	64.19	0.15	0.02	0.13	-224.18	13.3
6	120.52	1.04	64.65	0.23	0.02	0.21	-283.75	8.7
7	139.82	1.35	64.90	0.26	0.02	0.24	-303.80	7.7
8	110.13	0.92	66.44	0.20	0.01	0.19	-247.58	5.0
9	115.23	1.07	65.80	0.16	0.01	0.15	-262.67	6.3
10	99.85	0.67	63.58	0.23	0.02	0.21	-226.80	8.7
11	130.83	1.31	65.02	0.18	0.01	0.17	-241.29	5.6
12	135.14	1.14	66.63	0.19	0.03	0.15	-245.85	15.8
13	125.18	1.01	64.35	0.19	0.02	0.17	-248.35	10.5
14	141.69	1.20	71.53	0.29	0.01	0.28	-404.71	3.5
15	135.08	1.52	66.54	0.18	0.01	0.17	-257.12	5.6
16	123.17	0.93	66.94	0.24	0.02	0.22	-345.76	8.3
17	144.83	1.70	65.56	0.24	0.03	0.21	-276.21	12.5
18	119.00	1.04	65.84	0.18	0.01	0.17	-338.58	5.6
19	136.22	1.22	69.99	0.26	0.01	0.25	-434.44	3.9
20	123.37	1.06	66.44	0.16	0.00	0.16	-249.89	0.0
21	109.53	1.12	61.48	0.17	0.01	0.14	-181.02	5.9
22	119.40	1.30	61.82	0.18	0.03	0.15	-221.76	16.7
23	110.02	1.04	57.44	0.12	0.02	0.11	-141.40	16.7
24	122.81	0.97	60.74	0.16	0.01	0.15	-179.61	6.3
25	96.44	2.25	57.26	0.21	0.06	0.15	-159.30	28.6
26	120.80	1.69	61.68	0.21	0.03	0.18	-221.09	14.3
27	112.85	0.95	60.17	0.18	0.03	0.14	-210.57	16.7
28	105.59	0.92	60.48	0.13	0.00	0.13	-182.54	0.0

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX G. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR ELDERLY WOMEN AT A LOUD INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	246.48	3.26	72.69	0.09	0.00	0.09	-213.35	0.0
2	262.49	4.44	67.56	0.14	0.04	0.10	-197.09	28.6
3	221.22	2.51	70.04	0.09	0.00	0.09	-218.47	0.0
4	241.13	4.02	65.67	0.08	0.00	0.08	-145.79	0.0
5	213.46	2.64	66.16	0.06	0.00	0.06	-123.83	0.0
6	225.41	2.24	64.71	0.16	0.05	0.12	-184.89	31.3
7	168.73	1.40	70.44	0.14	0.01	0.13	-261.78	4.2
8	194.86	2.25	65.75	0.08	0.00	0.08	-139.26	0.0
9	231.48	3.38	64.86	0.09	0.01	0.08	-153.98	11.1
10	231.75	2.56	68.36	0.08	0.00	0.08	-160.30	0.0
11	245.73	4.18	65.94	0.16	0.07	0.09	-136.37	43.8
12	221.77	3.18	65.02	0.11	0.02	0.09	-140.69	18.2
13	232.44	3.35	65.13	0.11	0.02	0.09	-171.76	18.2
14	197.56	3.58	58.11	0.06	0.03	0.04	-89.11	50.0
15	175.16	2.01	58.82	0.06	0.01	0.06	-98.15	16.7
16	186.61	2.17	59.70	0.06	0.01	0.05	-96.04	16.7
17	205.08	3.90	58.44	0.11	0.04	0.07	-122.32	36.4
18	155.59	2.57	58.67	0.08	0.03	0.06	-105.67	37.5
19	185.97	2.60	60.88	0.11	0.02	0.09	-122.92	18.2
20	203.59	2.37	61.73	0.10	0.01	0.09	-116.52	10.0
21	243.34	3.87	65.39	0.14	0.03	0.10	-170.20	21.4
22	200.70	2.21	60.70	0.09	0.02	0.07	-124.75	22.2
23	225.75	3.26	59.87	0.09	0.01	0.08	-94.52	11.1
24	314.58	5.93	63.99	0.09	0.03	0.06	-120.23	33.3
25	264.78	4.99	64.80	0.15	0.01	0.15	-164.72	6.7
26	233.74	3.46	60.84	0.11	0.03	0.08	-137.10	27.3
27	200.14	3.23	64.31	0.11	0.04	0.07	-153.25	36.4
28	219.90	2.67	70.70	0.08	0.00	0.08	-176.76	0.0

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow (%).

APPENDIX H. ADJUSTED MEANS AND STANDARD DEVIATIONS OF ACOUSTIC AND AERODYNAMIC MEASUREMENTS FOR ELDERLY MEN AT A LOUD INTENSITY LEVEL.

Subject	Fo	Fo SD	SPL	Peak	DC	AC	MFDR	DC/PK
1	128.69	1.55	66.90	0.31	0.04	0.28	-286.66	12.9
2	128.76	1.88	66.27	0.40	0.06	0.33	-363.56	15.0
3	187.76	2.85	69.57	0.21	0.04	0.18	-281.79	19.1
4	129.35	1.24	65.83	0.18	0.01	0.18	-243.22	5.6
5	139.89	1.16	67.48	0.26	0.03	0.23	-239.22	11.5
6	143.18	1.84	63.38	0.13	0.01	0.12	-176.77	7.7
7	141.81	1.84	64.96	0.20	0.02	0.18	-232.93	10.0
8	96.38	1.13	65.41	0.21	0.02	0.19	-256.66	9.5
9	108.96	1.21	64.63	0.25	0.04	0.22	-280.11	16.0
10	143.54	1.77	65.02	0.20	0.03	0.17	-218.26	15.0
11	122.34	2.16	66.89	0.21	0.02	0.18	-225.16	9.5
12	113.55	0.96	65.02	0.28	0.05	0.23	-247.52	17.9
13	130.86	1.85	61.78	0.15	0.01	0.14	-152.78	6.7
14	132.78	1.46	61.94	0.21	0.03	0.19	-187.80	14.3
15	131.43	1.41	65.96	0.14	0.01	0.14	-206.88	7.1
16	177.62	3.16	63.36	0.17	0.04	0.14	-180.97	23.5
17	120.64	1.49	59.55	0.15	0.02	0.13	-143.24	13.3
18	125.21	1.84	64.28	0.20	0.02	0.18	-202.66	10.0
19	95.97	1.30	56.37	0.17	0.04	0.13	-142.46	23.5
20	142.65	1.57	65.35	0.18	0.02	0.16	-229.36	11.1
21	126.47	1.22	63.31	0.21	0.02	0.19	-134.65	9.5
22	127.42	1.21	61.45	0.15	0.02	0.12	-145.85	13.3
23	111.21	1.00	62.40	0.17	0.02	0.16	-175.15	11.8
24	115.02	1.69	59.37	0.23	0.03	0.19	-168.03	13.0
25	128.51	1.50	59.85	0.25	0.07	0.19	-188.45	28.0
26	149.74	1.51	71.18	0.24	0.02	0.22	-352.61	8.3
27	143.76	1.43	64.78	0.24	0.03	0.20	-274.70	12.5
28	177.20	1.99	65.82	0.26	0.08	0.18	-278.58	30.8

Fo = fundamental frequency (Hz); Fo SD = fundamental frequency standard deviation (Hz); SPL = sound pressure level (in RMS); Peak = peak glottal airflow (l/s); DC = minimum glottal airflow (l/s); AC = alternating glottal airflow (l/s); MFDR = maximum flow declination rate (l/s/s); DC/PK = the ratio of minimum glottal airflow/peak glottal airflow(%).

APPENDIX I. COEFFICIENT OF VARIATION FOR THE ACOUSTIC AND AERODYNAMIC MEASURES ACCORDING TO SUBJECT GROUP AND INTENSITY CONDITION.

	Fo	Fo SD	Peak	DC	AC	MFDR	DC/PK
Comfortable							
Young Women	9.56	3.93	22.22	66.68	20.00	37.52	30.56
Elderly Women	17.92	4.04	30.00	66.67	28.57	48.27	58.33
Young Men	12.74	10.48	28.57	50.00	25.00	51.44	43.75
Elderly Men	20.20	7.42	37.50	66.67	23.08	45.87	35.00
Loud							
Young Women	8.14	3.96	20.00	100.00	14.29	19.95	60.00
Elderly Women	14.99	3.85	30.00	100.00	42.85	27.98	17.65
Young Men	10.97	10.76	21.05	50.00	33.33	27.20	70.00
Elderly Men	16.33	7.58	28.57	66.67	38.46	27.35	53.85

BIOGRAPHICAL SKETCH

Mary Margaret Gorham-Rowan was born in Belle Glade, Florida on July 20th, 1966. Her family moved to Ft. Pierce, Florida, where she resided until graduation from high school in 1984. She was subsequently admitted to Florida State University in Tallahassee, Florida, where she earned a Bachelor of Science degree in Speech Pathology and Audiology in 1988, and a Bachelor of Arts degree in Spanish in 1989. She continued her education by enrolling in the Master of Science program for Speech-Language Pathology at Florida State University, and was granted the degree in 1991. In January 1993, she was admitted full-time to the University of Florida to begin doctoral studies in the areas of Voice and Swallowing. Following relocation to Tallahassee, Florida in July 1996, she continued her doctoral studies on a part-time basis. She was married to William Riley Rowan on October 28th, 2000. In January 2001, she moved to Atlanta, Georgia to accept the position of Assistant Professor in the area of Voice and Swallowing in the Communication Disorders Program at Georgia State University, where she is currently employed.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Christine M. Sapienza, Chair
Professor of Communication Sciences and Disorders

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William S. Brown, Jr.
Professor of Communication Sciences and Disorders

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Howard B. Rothman
Professor of Communication Sciences and Disorders

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Professor of Anatomy and Cell Biology

This dissertation was submitted to the Graduate Faculty of the Department of Communication Sciences and Disorders in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 2002

Dean, Graduate School